USDA

ARS

ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

2001

U.S. Water Conservation Laboratory

WATER SAVED IS WATER EARNED

Phoenix, Arizona

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

2001

U.S. WATER CONSERVATION LABORATORY
U.S. Department of Agriculture
Agricultural Research Service
4331 E. Broadway Road
Phoenix, Arizona 85040

Telephone: (602) 437-1702
FAX: (602) 437-5291
E-mail: bclemmens@uswcl.ars.ag.gov
Website: www.uswcl.ars.ag.gov

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Director's Message

2001 was a year of planning. Six of the seven major research projects at the laboratory were in various stages of ARS's new peer review process by the Office of Scientific Quality and Review (OSQR). Five were approved during 2001, and one is still under review. The remaining research project will be reviewed during 2002. Because of the amount of effort devoted to developing these research plans, we thought it would be useful to provide them in our Annual Research Report. These plans will inform the audience for this report what we intend to do over the next five years. The research staff is excited about their new plans, and we look forward to making positive contributions to science and agriculture.

Over the past several years, we have been trying to bring together the remote sensing and the irrigated farm management teams to build on each other's strengths. Such a merger happened this year as we organized our research plans. As a result, Doug Hunsaker (70%) and Floyd Adamsen (30%) joined a new project entitled "Irrigated crop management utilizing remote sensing." Doug will lead the effort to determine crop coefficients from remote sensing data. Floyd will assist the group with development of nitrogen management recommendations based on remote sensing data. This shift resulted in Doug's being moved from the Irrigation and Water Quality Research Unit to the Environmental and Plant Dynamics Research Unit. Besides the past remote sensors [(Paul Pinter, lead scientist (70%); Ed Barnes (100%), Glenn Fitzgerald (100%)], Bruce Kimball (20%) and Gary Wall (10%) also will bring additional micro-meteorological and plant physiological expertise to the new project. We expect this new level of cooperation to provide useful farm management tools based on remote sensing.

We welcomed two new staff members to the lab in 2001: Fedja Strelkoff and Glenn Fitzgerald. Fedja had worked at the lab since 1991, but most of that time was as an employee of the University of Arizona. He is now lead scientist for the new research project "Surface irrigation water quality and management." He has been instrumental in development of our surface irrigation models and now will take a more leading role in both development and application of the models. Glenn comes to us from Shafter, California, where he worked for ARS conducting research on remote sensing with hyperspectral radiometers. He joins the remote sensing team at the laboratory on their new project "Irrigated crop management utilizing remote sensing." Glenn will continue his work with hyperspectral radiometers to detect various forms of plant stress. Welcome Fedja and Glenn.

Sherwood Idso retired from the lab after 34 years. He spent his entire, very productive career at the laboratory. A dedication is included in this report. We wish Sherwood well in his new ventures.

The laboratory program looks strong and healthy in the near term. In the long term, we need to focus on developing technology that will help growers and water-resource managers to effectively utilize water for the good of the community. This will require increased cooperation with users and additional resources. Leveraging our current resources and strong research program will be needed to bring this about.

Bert Clemmens
Laboratory Director

Dedication

Sherwood B. Idso's career began at the U.S. Water Conservation Laboratory in June of 1967 as a research physicist. He had just come from the University of Minnesota, where he received his B.S. in physics, his M.S. in soil science with a minor in physics, and his Ph.D. in soil science with minors in meteorology and mechanical engineering.

In the early part of his career, Sherwood developed several methods for measuring and estimating (1) net, solar and thermal radiation fluxes, (2) near-surface water contents of bare and vegetated soils, and (3) daily evaporative water losses from bare and vegetated surfaces. He determined how water vapor and airborne particulates affect the solar and thermal radiation balances at the Earth's surface. The latter led to an interest in studying dust devils and also haboobs, the huge dust storms that roll in from the desert.

Sherwood and other USWCL colleagues developed remote sensing techniques for measuring several important plant and soil properties. This led to the use of infrared themometry and the concept of the crop water stress index, whereby foliage temperatures could be used to schedule irrigations.

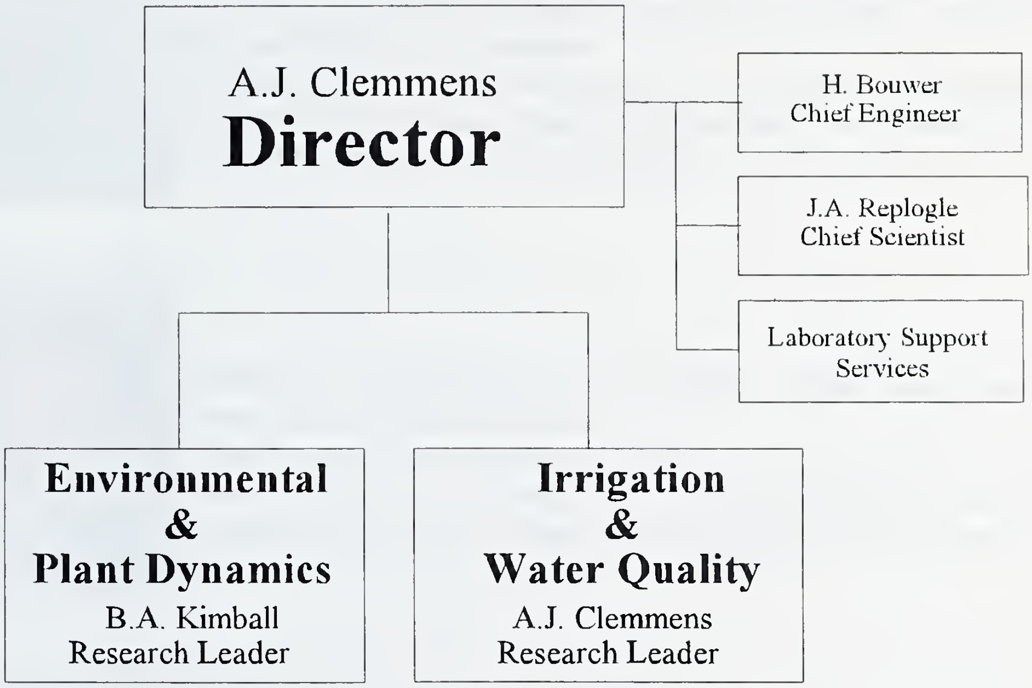
Sherwood became interested in the debate regarding the degree to which Earth's temperature may rise due to the increasing atmospheric CO_2 concentration. He argued that any global warming would be much less than predicted by climate modelers. However, an elevated concentration of CO_2 also affects plant growth, and together with colleagues, Sherwood also conducted many experiments to determine the direct effects of elevated CO_2 on agricultural productivity and water use. Started in 1987, the experiment with orange trees is the longest ever conducted, and Sherwood continues to collaborate on it while in retirement.

Sherwood was one of the USWCL's most productive scientists, authoring more than 480 publications as part of his official duties and 88 more on his own time, including a pair of influential books on carbon dioxide and global change. His papers have been cited in the scientific literature in excess of 6500 times, which is more than an order of magnitude above the norm for all scientists.

Sherwood retired to a new career reviewing literature about CO_2 and writing editorials for the Center for the Study of Carbon Dioxide and Global Change, which are published weekly on the Web (www.co2science.org). We dedicate this 2001Annual Research Report to him, and we wish him well in his new endeavor -- unfettered by reviews, approvals, and Form 115s!

LABORATORY PROGRAM

Laboratory Organization



Mission

The mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing better methods for scheduling irrigations, developing the use of remote sensing techniques and technology, protecting groundwater from agricultural chemicals, commercializing new industrial crops, and predicting the effect of future increases of atmospheric CO_2 on climate and on yields and water requirements of agricultural crops.

LABORATORY MANAGEMENT

ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow; surface and groundwater relations.

JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

BRUCE A. KIMBALL, B.S., M.S., Ph.D., Research Leader for Environmental and Plant Dynamics and Supervisory Soil Scientist
Effects of increasing atmospheric CO_2 and changing climate variables on crop growth and water use; free-air CO_2 enrichment (FACE) and CO_2 open-top chambers and greenhouses; micrometeorology and energy balance; plant growth modeling.

LABORATORY SUPPORT SERVICES

ELECTRONICS ENGINEERING LABORATORY

D.E. Pettit, Electronics Engineer

The electronics engineering laboratory is staffed by an electronics engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U.S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase, and upgrade of electronic equipment. Following are examples of work performed in 2001:

- Completed designing and implemented use of the software for the Generation II(GEN II) probes which measure flood irrigation water advance and recession dates and times.
- Designed the GEN III probe utilizing a surface-mount microcontroller that is flash programmable and interfaceable to a new 24-cm variable water detection transducer.
- Wrote new software programming to accommodate new advances in the microcontroller hardware being implemented in the new GEN III probe.
- Designed a 24-cm low-power optics source/detector transducer using surface mount technologies to interface to the GEN III probe. Designed, constructed, and experimented with several optic transducers for variable water level detection.
- Designed and assisted in the construction of the mold for a 24-cm multiple optic transducer for the Gen III probe and also constructed several 24-cm transducers.
- Designed and constructed several visual test displays to control and read the 24-cm transducers.
- Continued designing schematic capture parts and circuit board footprints for the appropriate ORCAD libraries.
- Repaired LPKF circuit board mill machine and updated the hardware.
- Continued performing multiple tests of the 10 fiber optic sensing GEN II probes with acceptable results.

LIBRARY AND PUBLICATIONS

Lisa DeGraw, Publications Clerk

Library and publications functions, performed by one publications clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, and publications co-authored with outside researchers, as well as holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the staff. Library holdings include approximately 2600 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U.S. Water Conservation Laboratory List of Publications, containing over 2300 entries, is maintained on ProCite, an automated bibliographic program. The automated system provides for

sorting and printing selected lists of Laboratory publications and is now accessible on LAN by the Research Staff and on the USWCL home page (www.uswcl.ars.ag.gov) by the public. Publications lists and most of the publications listed therein are available on request.

We are in the process of converting publications into pdf files which will allow easy access to our lab publications through our home page on the web. There are currently approximately 200 publications available for public use.

COMPUTER FACILITY

T.A. Mills, Computer Specialist

The computer facility is staffed by one full-time Computer Specialist and one full-time Computer Assistant. Support is provided to the ARS Phoenix Location, including the U.S. Water Conservation Laboratory (USWCL), the Phoenix Location Administration Office, and the Western Cotton Research Center (WCRL).

The facility is responsible for designing, recommending, purchasing, installing, configuring, upgrading, and maintaining the Phoenix Location's Local and Wide Area Networks (LAN, WAN), computers, and peripherals. The USWCL LAN consist of multiple segments of 10 Base-T, 100 Base-T, 1 Gigabit hubs and switches. The LAN is segmented using a high speed switches. Segments are made up of fiber optics, CAT 5 and standard Ethernet. This configuration currently provides over 200 ports to six USWCL buildings plus those at WCRL. Internet service is provided by Arizona State University (ASU) via a Point-to-Point T-1 line. The facility maintains two Internet domains uswcl.ars.ag.gov, and wcrl.ars.usda.gov. The Laboratory LAN is comprised of several servers operating under Windows NT 4.0. End users operate mainly under Windows 95, 98, 2000, and Windows NT 4.0 with a few OS/2 workstations. Security is currently being provided through the USWCL router. A Cisco PIX firewall is in the process of being implemented.

Services such as print, file, remote access, and backup are provided by the USWCL LAN. Other services such as DNS and E-Mail are provided to both the USWCL and WCRL. The USWCL maintains Web Servers for both USWCL (www.uswcl.ars.ag.gov) and WCRL (www.wcrl.ars.usda.gov). Currently FTP access is restricted to local accounts. This policy may be relaxed during the coming year.

MACHINE SHOP

C.L. Lewis, Machinist

The machine shop, staffed by one machinist, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U.S. Water Conservation Laboratory research projects. The following are examples of work orders completed in 2001:

- Constructed mold for a 24-cm multiple optic transducer for the GEN III probe, as described in the electronics section above, and adjusted specification where necessary.

- Constructed an adapter which fits on an automatic polishing machine arm for polishing the ends of a 3-mm fiber optic light pipe.
- Manufactured multiple sample cup and cap for ball grinding of plants and soil samples.
- Manufactured a catch release tool for removing rubber hoses from bulkhead fittings.

USWCL OUTREACH ACTIVITIES

The USWCL staff participates in numerous activities to inform the public about ARS and USWCL research, to solicit input to help guide the USWCL research program, to foster cooperative research, and to promote careers in science.

"Experiments for the Classroom." The USWCL web site (www.uswcl.ars.ag.gov/events/exper/exper.htm) contains experiments suitable for high school science classes.

Support for Minority Graduate Student. The Irrigation and Water Quality MU supports an Hispanic graduate student in an assistantship at the Agricultural and Bio Engineering Department, University of Arizona.

Program for Moroccan Visitors, February 9. USWCL and Western Cotton Research Laboratory staff presented and discussed their respective research, focusing on cooperation with universities, with Mohamed Kamal and Mohamed Moussaoui from the Moroccan Institut National de la Recherche Agronomique and Recherche Agronomique de Meknes, respectively.

6th Annual Vegetable Crops Field Day, February 13. Ed Barnes gave a presentation on using remote sensing to monitor irrigation, fertility, and pest incidence levels in crops. The event was hosted by the University of Arizona Cooperative Extension.

"Water & Science Ag-Ventures," February 15 & 16. USWCL, in cooperation with the University of Arizona Maricopa Agricultural Center (MAC) and the Natural Resource Education Center of the Natural Resources Conservation Service, sponsored "Water & Science Ag-Ventures," an annual educational program for junior and high school students, held at MAC, near Maricopa, Arizona. The USWCL staff provided hands-on demonstrations based on USWCL research programs, with an accompanying brochure to be pursued further in the classroom. The students also received information on careers in science, specifically in ARS. USWCL's partners in the event provided hands-on experience with an actual irrigation event and a tour of the MAC aquaculture ponds.

Arizona Ag Day, February 28. The USWCL continued its participation in the annual Arizona Agricultural Day (Ag Day) in downtown Phoenix. The purpose of Ag Day is to inform the public of the importance of agriculture in their daily lives. The theme is "Arizona Agriculture, Something You Should Know About." The exhibit featured an ARS backdrop depicting a variety of ARS research areas; handout materials such as "Science in Your Shopping Cart," *Agricultural Research* magazine; and displays and materials on USWCL research. The exhibit also included educational and career materials for teachers and students. Several thousand people attended the event, and the ARS exhibit was well attended.

Bring-Your-Child-to-Work Day, April 26. Twenty-one children, ages 6 to 16, participated in "Bring-Your-Child-to-Work Day" at the U.S. Water Conservation Laboratory and Western Cotton Research Laboratory in Phoenix. The staffs of the two laboratories provided a full morning's

participatory program that related the science to the children's day-to-day lives. In addition to the planned program, the children also spent time at their parent's work site. The Location Administrative Office coordinated and assisted with the day's activities that included a festive outdoor picnic lunch.

Planning Workshop for Joint Chinese-Japanese CO_2 Project, March 5-8. Bruce Kimball participated in a workshop at Nanjing and Wuxi, China, to plan a joint Chinese-Japanese Free-Air CO_2 Enrichment (FACE) project on rice and wheat.

Visit by Mexican Students, March 6. Eduardo Bautista, Fedja Strelkoff, and John Replogle provided a program on USWCL research on irrigation for students from the University of Chapingo, Mexico.

Visitors from India, March 14. Sherwood Idso met with visitors from India who were seeking information on carbon sequestration and other areas related to global climate change.

Training for South African Student, March 18-24. Terry Coffelt provided a one-week training session for a South African graduate student working on an MS degree in South Africa. The student was sponsored by international affiliates to study the production and seed harvesting of the Guayule plant. He hopes to duplicate the success of this plant's resources in his home country.

Summer Agricultural Institute for Teachers, June 22. Ed Barnes and Shirley Rish provided an ARS and USWCL exhibit at the week-long Summer Agricultural Institute for 32 elementary and junior high teachers. The program encourages teachers to incorporate agricultural information into school curricula. Materials distributed at the USWCL exhibit included information on careers in science and ARS and experiments that can be done in the classroom.

Minority Technician Recruited, July. The Environmental & Plant Dynamics MU recruited a minority technician for a two-year term appointment.

Attendance at EEO Conference, September 4-7. Rich Lee, Location Administrative Office ; and Skip Eshelman and Carl Arterberry attended the EEO Quad Conference in Concord, California.

Annual Conference to Advance Chicanos/Latinos and Native Americans in Science, September 27-30. Representatives of the USWCL, Western Cotton Research Laboratory, and Phoenix Location Administrative Office participated in the annual conference of the Society for the Advancement of Chicanos/Latinos and Native Americans in Science (SACNAS), which was held in Phoenix, Arizona. ARS scientists spoke at symposia detailing career opportunities with ARS and hosted a field tour of the Phoenix location with demonstrations of ongoing research projects. Phoenix location representatives also helped staff the ARS exhibit booth at the conference.

ARS Irrigation and Drainage Exhibit at the International Irrigation Show, November 2-4. Shirley Rish coordinated an exhibit on irrigation and drainage research at the annual Irrigation Association International Show in San Antonio, Texas. John Replogle provided display materials and

helped staff the exhibit. ARS scientists from Florence, South Carolina; Bushland, Texas; Baton Rouge, Louisana; Ft. Collins, Colorado; Stoneville, Mississippi; and the National Program Staff also assisted. The exhibit was supported by Dale Bucks, ARS National Program Leader for Water Quality and Management. The Irrigation Association provided complimentary exhibit space. Registered attendance was more than 6000, and the ARS exhibit was well attended.

Seminar at Grand Canyon University, November 16. Bert Clemmens gave a seminar, "Finding your Way Through the Fog--Expanding the Frontiers of Engineering and Science," to a group of 30 students and faculty in the College of Science at Grand Canyon University.

Visitors from Central Asian Countries, Nov. 30. Representatives of government ministries for natural resources, water, environment, and foreign affairs from Kazakhstan, Kyrgystan, Tajikistan, Turkmenistan, and Uzbekistan visited USWCL on a tour under the International Visitor Program of the U.S. Department of State. These governments are seeking the most efficient ways to manage their water resources. Presentations and discussions focused on integrated water management and included global perspectives, climate change, dams, artificial recharge of aquifers for underground storage of water, water banking, water reuse, virtual water, efficient irrigation, and water measurement.

Training and Learning Opportunities for Minority Students. USWCL continued to provide training and learning experiences for part-time minority student employees from Arizona State University.

SAFETY

T. Steele

The Laboratory Safety Committee enjoys well-deserved respect from the employees. It is a time-consuming commitment and requires judicious management of time and work priorities. Serving on the safety committee, however, is gratifying in terms of its record of accomplishments. A few examples of our accomplishments follow:

a. A program for the installation and use of Automatic External Defibrillators (AED) was developed and implemented. The AED has been installed and is available for use. A first responder team has been identified, and they are in the process of finalizing notification and response procedures. The City of Phoenix Fire Department Emergency Access Services Department has been notified of the installation.

b. The Safety Committee's project of gathering information for inclusion into a database that the Phoenix Fire Department uses in a emergency response data base in ongoing.

c. Increased security measures have been implemented, and additional measures to control access to the facility buildings and grounds are being considered.

d. Employees are still encouraged to report all safety concerns, even those that might seem trivial.

e. The committee takes its duties seriously and has worked diligently to insure compliance with all EPA and OSHA regulations and radiological safety protocols.

The location staff thanks the committee for their good work on our behalf and looks forward to another year of safety awareness and exemplary records.

STUDENTS AT USWCL

J. Askins

The USWCL has enjoyed a mutually beneficial relationship with students from nearby Arizona State University over the years. Students come under work-study agreements and student federal appointments. They perform a variety of tasks from collecting samples to solving computer problems, from numbering vials to writing protocols, from weighing soil to processing and analyzing non-soil data. Students who work in the clerical/administrative area have worked in personnel and safety areas as well as doing general clerical work such as filing and copying. Operation of ARS automated systems, publication clerk duties, and literature searches are also performed.

The students benefit from the income and experience, and we benefit from their enthusiasm, up-to-date expertise, and energy. Some have stayed on after graduation, even earning Ph.Ds. under ARS assistance programs.

IRRIGATION
&
WATER QUALITY
MANAGEMENT UNIT

I&WQ Organization

- **IRRIGATION & WATER QUALITY**
  A. J. Clemmens
  Research Leader
  - **WATER PROJECT MANAGEMENT**
    - A. J. Clemmens, Research Hyd Enguneer
    - E. Bautista, Research Hyd. Engineer
    - J. A. Replogle, Research Hyd. Engineer
    - R. J. Strand, Electrical Engineer
    - B. T. Wahlin, Civil Engineer
  - **IRRIGATED FARM MANAGEMENT**
    - T. S. Strelkoff, Soil Scientist
    - F. J. Adamsen, Soil Scientist
    - E. Bautista, Research Hyd Engineer
    - A. J. Clemmens, Research Hyd. Engineer
    - R. J. Strand, Electrical Engineer
    - H. Tabbara, Soil Scientist
  - **WASTEWATER IRRIGATION**
    - H. Bouwer, Research Hyd Engineer
    - N. L. Duran, Microbiologist

Mission

The mission of the Irrigation and Water Quality (I&WQ) Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit addresses high priority research needs for ARS's National Programs in the area of Natural Resources & Sustainable Agricultural Systems. The unit primarily addresses the Water Quality and Management National Program. It also addresses the application of advanced technology to irrigated agriculture.

I&WQ RESEARCH STAFF

FLOYD J. ADAMSEN, B.S., M.S., Ph.D., Soil Scientist
Management practices that reduce nitrate contamination of groundwater while maintaining crop productivity; application of 100% irrigation efficiency; winter crops for the irrigated Southwest that can be double-cropped with cotton; contributions of natural and urban systems to nitrate in groundwater.

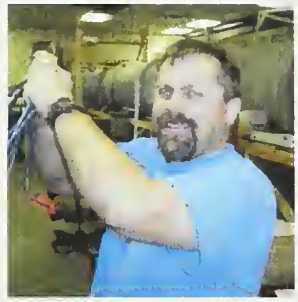
EDUARDO BAUTISTA, B.S., M.S., Ph.D., Research Hydraulic Engineer
On-farm irrigation system hydraulic modeling; hydraulic modeling of irrigation delivery and distribution systems; control systems for delivery and distribution systems; effect of the performance of water delivery and distribution systems on-farm water management practices and water-use efficiency; integrated resource management and organizational development for irrigated agricultural systems.

HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow, surface water-groundwater relations.

ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

NORMA L. DURAN, B.S., Ph.D., Microbiologist
Wastewater irrigation; molecular detection of waterborne pathogens; pathogen regrowth and disinfectant by-product formation in distribution systems; fate and transport of pathogens in the subsurface environment.

JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.



ROBERT J. STRAND, B.S., Electrical Engineer
Automatic control of irrigation delivery systems; development and integration of field sensors, intelligent field hardware, USWCL feedback and feedforward control software, and commercial supervisory control software to create a plug-and-play control system.

THEODOR S. STRELKOFF, B.C.E., M.S., Ph.D., Research Hydraulic Engineer
Surface-irrigation modeling: borders, furrows, two-dimensional basins; erosion and deposition; design and management of surface-irrigation systems; canal-control hydraulics; flood-routing methodologies; dam-break floodwaves; flow in hydraulic structures.

BRIAN T. WAHLIN, B.S., M.S., Civil Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

MANAGEMENT OF WATER SUPPLIES FOR IRRIGATION

Albert J. Clemmens, Research Hydraulic Engineer
John A. Replogle, Research Hydraulic Engineer
Eduardo Bautista, Research Hydraulic Engineer
Robert J. Strand, Electrical Engineer
Brian T. Wahlin, Civil Engineer

PROJECT SUMMARY

Water supplies are limited in many areas of the country, particularly in the arid west where irrigated agriculture is the largest user of fresh water. Expanding urban populations and environmental water needs will potentially reduce water available for irrigation in the future. Water users are faced with requirements to more accurately document water uses and return flows. Water measurement and control in irrigated agriculture has experienced significant advances over the last two decades, yet further advancement is both possible and needed. Under this research project, we intend to develop improved water measurement technology, improved water accounting methods, and improved water control technology. New measurement methods will be developed for steep, sediment laden channels, channels with little or no head available, low-head pipelines (culverts), and submerged radial gates. A new canal automation system will be released to a CRADA partner to provide greater water control and operational flexibility to meet user needs. Water balance methods will be further developed to assist water purveyors with documenting water use, including methods to determine sources of error, which indicate where measurement effort should be focused.

OBJECTIVES

1. Flow Measurement and Accounting: We will develop a series of improvements to existing methods for measuring water flow rates and volumes in rivers, streams, canals, and culverts (low pressure or not flowing full). A series of laboratory studies is planned for currently identified water measurement problems (see research approach). We will continue to support software developed for design and calibration of long-throated flumes, will cooperate with customers to evaluate their water measurement and accounting methods, and will work toward solutions to their flow measurement problems.

2. Water Control: We will develop a series of methods, hardware, and software for improving the control of water in open-channel distribution systems typical of irrigation projects or large water supply projects. A new canal automation system currently under development will be turned over to our CRADA partner. The mechanical/hydraulic controller (DACL), used to maintain constant flow rates at canal offtakes, will be improved to make it more usable in remote sites.

NEED FOR RESEARCH

Description of Problem to be Solved

Competition for limited water resources among various users is increasing in many areas of the country, but particularly in the arid west. Irrigated agriculture is the largest user of fresh water resources and, thus, it needs to improve its water management (CAST 1996, National Research Council 1996). Important elements for improving agricultural water management are improved measurement, control, and ultimately, accountability of water resources at the irrigation project level. Water uses at the project or hydrologic unit scale are often poorly documented making meaningful management of water supplies difficult. Also, water supplies for agriculture from large irrigation projects are often not controlled well, resulting in over-delivery to individual users and ineffective use at the farm level. As water moves downstream through various projects and uses, its

quality degrades as salts, trace metals, and other contaminants are concentrated, often to the point of being unusable or having a negative impact on the environment. The objectives of this project are to develop tools for improving the management of water supplies, particularly for irrigation.

Relevance to ARS National Program Action Plan

The research is part of National Program 201, Water Quality and Management. The project falls under Component 2, Irrigation and Drainage Management. Both objectives deal with agricultural water conservation and fit under Problem Area 2.3 (Water Conservation Management), Goal 2.3.1 (Water Conservation Technologies). The research also supports Goal 2.3.3 (Agricultural Water Conservation and Environmental Quality).

Potential benefits expected from attaining objectives

Large-scale water supplies will be better managed in arid regions with the tools developed here. Water measurement, accounting, and control will be improved in irrigated agriculture, supporting more rational analysis of the impact of irrigated agriculture on the environment and allowing more rational decisions by society about water allocation and use.

Anticipated Products

New technology is provided for improving the operation and management of water projects, including canal automation/control and water measurement/accounting technology.

Customers of the research and their involvement

Based on past successful technology transfer and the anticipated products, customers will include the U.S. Bureau of Reclamation (USBR), Natural Resources Conservation Service, U.S. Geological Survey, Army Corp of Engineers, Bureau of Indian Affairs, State Departments of Water Resources (particularly Arizona and California), land-grant universities, civil and agricultural consulting engineers, and water purveyors (water conservancy districts, irrigation districts, municipalities, etc.). We have cooperated with NRCS staff on the application of flow measurement technology and related research needs at all levels (field office to national) and in states across all regions of the country. Our main point of contact is Tom Spofford, Water and Climate Center, Portland OR (letter attached), who disseminates information widely within NRCS. With USBR, cooperation on water measurement and control has been mainly with the Water Resources Research Lab, Denver CO (Cliff Pugh, letter attached). They transfer our technology to regional and area offices through manuals and technical assistance programs. Research on water-balance methods has primarily been with the Lower Colorado Region of USBR (Steve Jones), who along with other regions are transferring this technology to water purveyors through their water conservation plans. Further planned activities with Paul Matuska (letter attached) are expected to have additional impact on water conservation plans. Several water purveyors (e.g., Salt River Project, Maricopa Stanfield I&D District, Imperial Irrigation District) have been directly involved in various studies and technology transfer activities since much of this research must be conducted within real, full-size water systems. Water meter, remote monitoring, and hydrologic instrumentation manufacturers have been

customers, which is expected to continue with this project (e.g., Automata, Global Water, Micrometer, Nu-Way Flume Co., Plastifab, etc.). Individual water users also will be customers, particularly for the water measurement devices.

SCIENTIFIC BACKGROUND

Water demands by a growing urban population, concern over protection of water quality and natural habitats, decreasing political support for subsidies to the agricultural sector, and Native American water claims are key factors that are forcing state and federal governments to examine more carefully how water is allocated and distributed in irrigated agricultural regions. This has implications for water measurement, control, and accounting. Policies and programs to promote better water management are constrained by incomplete understanding of the hydrology of irrigated regions and inadequate or insufficient data on water use.

The Central Valley Project Improvement Act (CVPIA) of 1992 is a recent example of legislation that potentially reallocates water supplies within a basin. CVPIA requires water users to develop water management plans (USBR 1999). Within these plans, all water diverted must be measured and accounted for. Guidelines for formulating the conservation plans did not exist when CVPIA was enacted and have gradually evolved over the last decade. Not surprisingly, irrigation districts in the Central Valley are struggling to develop accurate water budgets, even though improved water measurement and water control are required under these plans. The Bureau of Reclamation is in the process of instituting these requirements for water users in other regions, as well. The ability to measure and control water supplies and to properly account for the disposition of water is paramount to achieving the required level of management, as highlighted at a recent USCID conference "*Benchmarking Irrigation System Performance Using Water Measurement and Water Balances*" (Davids and Anderson, 1999).

A large percentage of agricultural water users receive their water supplies through networks of open channels. Most of these systems were originally built to deliver water at a fixed rate and fixed timing. Providing flexible and accurate water deliveries, so that users can match crop and on-farm irrigation demands, represents a significant water conservation opportunity (Cross 2000). In recent years, many U.S. irrigation districts have modernized their canal physical infrastructure and operational procedures in an effort to provide greater delivery flexibility and accuracy (Burt and Styles 2000). Although most open-channel distribution systems still cannot offer the flexibility needed for farmers to convert to pressurized farm irrigation systems, increasing flexibility without also improving control of the delivery system can result in an increase in water that is "unaccounted-for." One district in central Arizona (unofficially) reported unaccounted-for water as 30-35% of diversions. With an intensive water measurement program where several dozen water measurement devices were installed, unaccounted-for water was reduced to 10-15%. This district still has a policy of delivering 10% more water than ordered so that when fluctuations occur, they will still deliver at least the requested rate. The Arizona Department of Water Resources limits water duties to individual farmers. However, for those served from irrigation districts, they allow 10% more water to be diverted (ADWR 1999). Cost-effective technology is strongly needed for improving project water control.

Performance indicators for irrigation and drainage projects proposed over the last several decades were summarized by an ICID working group (Bos 1997). That group is currently preparing a manual on performance assessment (ICID 2000). Three groups of performance indicators are given, dealing with 1) water balance and operational issues (e.g., related to water measurement, accounting and control), 2) economic and social issues, and 3) drainage and sustainability issues. Completely different indicators are used for each specific purpose (i.e., there is no crossover). There are two dozen parameters to choose from, and many of these vary over a project spatially and temporally. No single performance parameter fully addresses water control or delivery service issues. For poorly operated schemes, deliveries to users are grossly inequitable . As operations improve, the focus shifts to proper timing of water deliveries, then to proper flow rate, then to ability to vary duration, then to ability to maintain a constant flow rate, and then to the ability of the irrigator to vary shut off and/or flow rate with short notice. As operations improve, the type of demands placed on the system shift. The result is a continuously moving and more refined target. As a result, the performance indicators needed to define adequate service change. Since the quantitative values of the various performance indicators also vary with the physical limitations imposed by the canal system, no one has been able to set target quantitative values for any of these performance indicators. Further, the link between operational and economic or sustainability performance indicators is site specific and thus not generally quantifiable.

In a complementary effort, Burt et al. (1997) suggest a new paradigm for evaluation of traditional performance parameters such as irrigation efficiency, including accurate geographic boundaries, a defined time period, and an accurate water balance. Clemmens and Burt (1997) show that the accuracy of project performance measures can be determined based on the accuracy of individual volume estimates. This provides information on which quantities have the most influence on the overall accuracy and therefore demand more attention. These methods have been applied to the Imperial and Coachella Valleys in several studies (TWG 1994 and WST 1998). Unfortunately these reports are not routinely available because of the political sensitivity involved. Poor understanding of the hydrology of irrigated areas and improper interpretation of terms such as irrigation efficiency (IE) has lead to the unfounded expectation that improved efficiency will provide additional water supplies (Burt et al. 1997), when often irrigation return flows are used downstream. Solomon and Davidoff (1999) describe the differences between field and project IE based on the amount of reuse that occurs within a project. Difficulties in accounting for water exacerbate this problem.

Flow Measurement and Accounting

A key obstacle to improved water measurement and accounting is the cost of measurement programs (e.g., instrumentation, data collection, maintenance, data analysis). Many irrigation districts measure and continuously monitor water diversions at key control points, but do not do so for delivery to individual users. In one study, Palmer et al. (1991) showed that water accounting was poor (17% of deliveries not billed) and water metering was inaccurate when flow rates were measured only once per day (average rate varied by 20%). Accuracy of volumetric estimates depends on the accuracy and frequency of individual measurements (Wahlin et al. 1997, and Thoreson et al. 1999). Reliable and inexpensive data collection and communication technologies are needed to overcome this financial barrier. There are also hydraulic difficulties; i.e., field conditions under which measurement is difficult, uncertain, and/or costly.

Many existing primary flow measurement devices have accuracy (±2 standard deviations) under ideal conditions that vary from ±0.1% to ±2% (primarily systematic errors). Under field conditions, with the addition of secondary devices (e.g. transducers that provide readout of primary device), accuracy degrades to ±3% to ±5% for an instantaneous reading. Repeated readings over time reduce the random errors, but the systematic errors remain. Non-ideal field installations often cause additional systematic errors. Each measurement site within a project will have a different systematic error, part of which can be considered random from site to site. Thus the overall accuracy of total volume from many measurement sites will be better than the individual sites. The Arizona Department of Water Resources requires that annual reporting of groundwater pumping have an accuracy of ±10%. This may give a total volume accuracy on the order of ±5 to ±10%. This is similar to the water balance accuracy for the Imperial Valley reported by WST (1998). The cost for measurement devices for small flows (up to 15 cfs) range from a few hundred dollars for flumes and weirs (up to $1000 when a transducer and logger or totalizer are added) to $500 to $1000 for common pipe meters.

On the Lower Colorado River, water used by individual users along the river is determined by a Decree Accounting Method (USBR 1998). Under this method, unmeasured return flows to the river (i.e., ungauged surface drains, subsurface flow, etc.) are determined as a percentage of diversion. This percentage of return flows is essentially a negotiated value. The Bureau of Reclamation is trying to develop a more scientifically-based method (LCRAS) to determine water use based on remote sensing, weather-based ET estimates, and river flows. There is currently no information on the accuracy of either the current or proposed accounting method.

While significant strides have been made over the last two decades in measuring open-channel flows with flumes and weirs, there are open-channel flow conditions where existing measurement devices are not adequate (Replogle 2000). Of particular concern are open channels where little head loss is available for measurement, but channels that are too steep and sediment laden will also be studied, subject to support from cooperators. Most of these measurement problems are for relatively small flows (particularly 10 cfs and below). A variety of critical-depth and super-critical-depth flumes have been developed for steep channels. Super-critical flumes pass sediment, but are difficult to calibrate. Critical depth flumes can be designed to pass normal bed-load sediment, but sediment dunes can bury them. Flow measurement in low-head situations generally requires measurement of velocities, the trick being finding ways to infer the "average" velocity from the "measured" velocity(s), and doing it at low cost and high accuracy (Replogle 2000). This applies also to low-head pipes and culverts. A CRIS search on water measurement and flow measurement (and not in soil, plants, etc.) identified only one related project, other than those from this management unit. This project was on cut-throat flumes, which we consider an inappropriate technology and discourage their use (USBR 1997). We know of no other research projects working on improving water measurement technologies.

Water Control

The state-of-the-art in canal automation and control was summarized through a special issue of the *Journal of Irrigation and Drainage Engineering* (vol. 124, no. 1, 1998), *An International Workshop on Regulation of Irrigation Canals* in Morocco (RIC 1997) and a recent *USCID Workshop on*

Modernization of Irrigation Water Delivery Systems (Clemmens and Anderson 1999). Various canal control theories have been proposed, some have been tested to a limited degree with simulation models, but few have been tested in the field. Automatic controls have been applied mostly to individual gate structures.

Most canals are currently operated under manual upstream water-level control. Under this scheme, water released from the headgate is routed downstream through a series of gates, each passing the flow through to keep it's upstream water level constant. The disadvantage of such systems is that any errors in flow settings end up at the tail of the canal. Improved routing (feedforward control) schemes are needed to improve this type of operation; e.g., gate stroking (Bautista et al. 1997). Even with improved routing, imprecise measurements and unknown disturbances can cause flow mismatches (spills or shortages) downstream. Such mismatches need to be corrected through feedback control (typically based on the downstream water levels). Remote control from a central location with Supervisory Control And Data Acquisition (SCADA) systems is becoming more and more common. Supervisory control allows operators to see what is happening throughout the system at once. However, such systems are based on the skill of the operator and the information available to him/her, and results have been mixed.

We have attempted to improve on existing open-loop (feedforward) routing schemes (Bautista et al., 1997; Bautista and Clemmens, 1999). We concluded that the gate-stroking method is not feasible in many situations since it causes excessive flow changes, sometimes exceeding canal capacity, sometimes requiring negative inflows. Simple routing based on volume changes and delay times can produce satisfactory water level control without excessive flow changes (Bautista and Clemmens, 1999). These procedures have only been tested with simulation and still require field testing.

Downstream water-level feedback control strategies adjust canal inflow upstream to eliminate flow mismatches. A variety of downstream control schemes have been proposed (Malaterre et al. 1998). The main ones of practical interest are simple proportional integral (PI) controllers, linear quadratic regulators (LQR and related LQG and similar optimal control methods), model predictive control (MPC), and neural network/fuzzy controllers. Currently, we are focusing only on PI, LQR, and MPC systems. A special class of LQR controllers allows for flexible design and simple tuning without the appearance of being a "black box" (Clemmens and Schuurmans 1999). In fact, this control theory can be used to design a series of simple PI controllers as well. We have used this method to design controllers for several canals, which have worked well under simulation testing (Clemmens and Wahlin 1999 and Clemmens et al. 1997). Limited field trials also suggest that these will work successfully (Strand et al. 1999).

Strelkoff et al. (1998) and Bautista et al. (1996) studied the influence of canal physical characteristics on canal controllability. These studies demonstrate that different canals respond differently to control actions. Thus, the performance of canal control methods is site specific. Because of this, the ASCE Task Committee on Canal Automation Algorithms developed a set of standard test cases with standard performance measures so that various algorithms could be directly compared (Clemmens et al. 1998). Because of the wide variety of performance parameters possible to describe water delivery performance and the varied requirement of different project, the task

committee chose to use water level control in the canal (rather than variations in delivery flow rate, etc.) as the basis for comparing different algorithms. Three performance parameters for the downstream water level in each canal pool were recommended: 1) the maximum absolute deviation; 2) the integrated absolute deviation (a measure of the effort required to reject a system disturbance); 3) the steady-state error over the last two hours of each test. A fourth parameter was recommended to penalize unnecessary flow changes: 4) the integrated absolute discharge change. For a given test, the maximum of any pool and the average value for all pools were to be compared for both the first and last 12 hours of each test. These tests had both scheduled and unscheduled flow changes. Tradeoffs between water level deviations and amount of flow changes were expected, particularly as a result of individual choices during the tuning of each controller (Clemmens and Wahlin 1999).

There are many situations where electrical power is not available to operate motorized gates. Hydraulic/mechanical automatic gate controllers have been in use in the arid southwest for nearly a century (Clemmens and Replogle 1987). These controlled-leak controllers have the disadvantage of a large decrement where the water level changes significantly for different gate flow rates. An improvement on this gate was developed by Clemmens and Replogle (1987), the so-called dual-acting controlled-leak (DACL) controller. These have not been adopted, partially because of their complexity. However, several recent improvements in gate designs may make them more useful (e.g., Langemann gates by Aqua Systems 2000 Inc.).

A CRIS search of active projects on canal automation showed no projects other than those of this research unit. Those currently conducting canal automation research are typically not part of the CRIS system; however, we are aware of several complementary research efforts in this area, including Irrigation Training and Research Center, Cal Poly, San Luis Obispo; Water Resources Research Lab, USBR, Denver; the Water Management Group at Delft Technical University, Delft, The Netherlands, and the canal automation group at CEMAGREF, Montpellier, France. In the area of water delivery, we identified two related projects: one at Colorado State University dealing with management issues (as opposed to physical control) and one at U. of Hawaii dealing with reallocation of supply. Several other projects dealing with project performance were found and will be discussed in the next section. A CRIS search of active projects on water project or water delivery and irrigation identified nine related research projects on project performance. Two are ARS projects (Riverside CA and Ft. Pierce FL), 3 are from Colorado State Univ., one is from Univ. California, Berkeley, 2 are from Univ Nevada, Reno, and one is from Texas A&M. Several of these deal with field-scale rather than project-scale issues. Several of these are complementary to the research proposed here. None duplicate the research proposed here. Results from those projects could have implications for the research conducted under this project, although indirectly.

NATIONAL COLLABORATION

This research project contributes to the ARS initiative on Drought and Water Scarcity. This initiative will provide a series of tools to assist farmers, water districts, cities, water resource managers, and government agencies in managing both periodic water shortages due to drought and the long-term decline in available water resources. Research under this initiative will develop drought mitigation and forecasting methods, water conservation and reuse technologies, and tools for water managers to plan effectively for the future. This research will examine water availability and use at watershed

and larger scales over both short and long time periods. The result will be specific tools to provide more effective use of the Nation's water supplies.

The objectives contribute to the initiative deliverable on improved water conservation technologies. No other ARS locations are conducting similar research, although many use the water measurement technology developed here. Other locations cooperating with this research include Riverside CA, Parlier CA, Kimberly ID, and Bushland TX.

APPROACH AND RESEARCH PROCEDURES

The research conducted under this project falls primarily in the area of "Technology Development" rather than "Experimental Observation," and thus is not driven by hypothesis testing. Even where observational studies (e.g., hydraulics lab studies) are performed, they are oriented toward defining useful relationship rather than confirming hypotheses.

Objective 1 - Flow Measurement and Accounting

Experimental Design

The intent of this research is to develop new flow measurement technology and extend the range of usefulness of existing technology. Our target is better than ±10% accuracy for an individual reading (random and systematic) and better than ±5% systematic errors, with costs that are similar to existing devices for the range of flows to be measured.

<u>Correcting unreliable velocity distributions in short culverts</u>: Upstream elbows, the pump head, or other pipe fittings that may produce a distorted flow profile that is detrimental to the proper installation and operation of commonly available pipe meters. In open channels, flumes must sometimes be installed closer to upstream disturbances than specified by standard installation recommendations. Methods to condition flows to present proper profiles to meters over a short distance, have been successful on some field trials. Examples include a large diameter orifice (opening 90% of pipe diameter) to control wall jets and surface skimmer to settle the water surface upstream from flumes. Such ad hoc "fixes" cannot be generally recommended or reliably repeated without further study. An existing 30 inch diameter concrete pipe in the hydraulics laboratory will be used to test various methods to overcome a variety of introduced disturbances (e.g., twisting flow, jet from partial open gate, etc.). These methods (orifices, wall fins, etc.) will be evaluated by measuring downstream velocity distributions. A pitot-tube array has been constructed to measure all velocity heads simultaneously so that swirling flow will not distort the results.

<u>Debris-shedding propeller meter for continuous monitoring in culverts</u>: Propeller meters have long been used in pipe flows. Low-head pipelines and culverts often contain debris and trash that thwart the use of propeller meters for all but intermittent use. We have tested a nose-hung propeller meter that appears to shed almost all debris when located in the center of the pipe. Commercially available propeller blades are usually on the order of 6 in. diameter or less. Use of these small propellers in large culverts facilitates debris shedding, but compromise the measurement because they are sensitive to the velocity distribution which is a function of roughness and other effects. Replogle and

Wahlin (2000) showed that an average velocity could be accurately estimated (within 3%) with two velocity measurement made at the centers of the two concentric areas of equal size (i.e., center ½ of center area and concentric ½ area, as shown in Figure 1). We plan to explore whether we can obtain accurate measurements with a small propeller meter in a large pipe regardless of velocity profile. Can one propeller be located to accomplish this? How large does it need to be? Are two propellers needed? and where should they be placed?

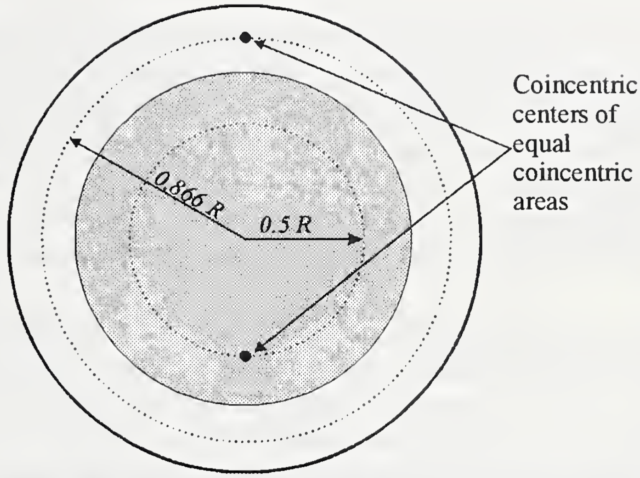


Figure 1. Two velocity measurements representing the centers of two concentric areas give a reasonable estimate of average velocity.

Surface-Velocity-Based Method: Measuring flows in flat sluggish canals is usually expensive when structural changes are required, for example raising the canal banks upstream. One of the oldest methods available is to measure the surface velocity with a single float. This has proven inaccurate (e.g., ±50%) and unreliable since the velocity of a single float cannot be related to average cross-section velocity. Historical work of Bazin (1865) and Replogle and Chow (1964) and application of turbulent velocity distribution models, such as the Seventh-Power Law and secondary currents (Schlichting, 1960), indicate that the location of the maximum velocity in a channel is influenced by the shape of the boundary and the boundary roughness and is located somewhat below the water surface. These references also indicate that this submerged maximum velocity may be reliably related to the average flow velocity, if the boundary roughness and channel shape can be characterized. A reliable indicator of the maximum velocity is needed to make this a viable flow measurement technique. The hypothesis is that if numerous floating particles are dumped simultaneously across a stream of interest, some of the particles statistically are likely to define the maximum surface flow element and that this maximum surface velocity can be related to the true maximum and hence the average velocity in the channel. Preliminary studies of a series of floating particles (e.g., sawdust, popcorn, or ice cubes) suggests that the average velocity is between 0.7 and 0.9 times the fastest particle velocity. This relationship should be a function of channel roughness. Preliminary data is shown in Figure 2. The spread in the particle velocities is also related to channel roughness. Thus

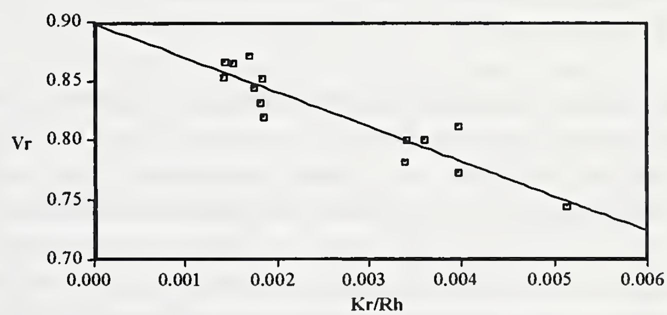


Figure 2. Relationship between the ratio of maximum surface velocity and the average channel velocity (Vr on the y-axis), and the ratio of the absolute roughness, Kr, and the hydraulic radius Rh (Kr/Rh on the x-axis).

by measuring the distribution of particle velocities, a more accurate estimate of average velocity may be possible. We propose to test these relationships in a series of small canals in Arizona with different relative roughness conditions, where accurate flow rates are available by other methods. Travel time for the fastest and slowest particles will be measured over a distance of 30 m. Relative channel roughness will be estimated by measuring the water surface gradient, cross sectional flow area, and discharge. This is intended for simple flow survey work, where ±10% accuracy is acceptable, since it might not be convenient for continuous monitoring.

Submerged Radial Gates: Gates and weirs are commonly used to control flows in irrigation canals; however, flow measurement with such devices is often inaccurate. There are a variety of ways to modify gate structures to make them more accurate measuring devices. We have developed calibrations for broad-crested weirs, leaf gates, etc. (Bos et al. 1984 and Wahlin and Replogle 1994). Radial gates pose an interesting challenge since their (unsubmerged) discharge coefficient tends to change with gate position. Submerged radial gates have proven even more difficult. Published submerged-gate calibration equations are insensitive and lead to large errors (e.g., ±50%). Furthermore, all calibration studies published on radial gates were conducted with a single gate and with the upstream and downstream channels of the same width as the gate. The calibration equations reflect this physical condition and are essentially not applicable under typical field conditions where the radial gate structure is placed in a much wider channel. Further, many large canals have banks of radial gates as check structures. If all gates are in the same position, then the published calibration equations have the best chance of being appropriate. However, for operational reasons, many such structures are operated with one or more gates closed and the others more fully open, particularly at low flows to avoid trapping debris.

We have conducted preliminary laboratory studies on a radial gate with a width less than half that of the approach and tailwater channels (Tel 2000). Free-flow studies confirmed prior relationships developed for the contraction coefficient (ratio of vena contracta depth to gate opening). We also found a useful relationship for the energy loss based on jet velocity head and Reynolds number. Then the energy (Bernouli) equation is sufficient to determine flow rate with no additional coefficients. Submerged calibration has proven more difficult. Because of the large energy loss downstream from the gate, as with a hydraulic jump, the momentum equation is more appropriate on the downstream side of the structure. Use of the momentum equation from the upstream to the downstream side requires estimates of all the forces (in the direction of flow) on the gate and walls. We chose to use the energy equation on the upstream side, since we have a useful relationship under free flow, and the momentum equation on the downstream side, since energy losses there are too difficult to estimate accurately. The equations are matched at the vena contracta, where we assume that the jet thickness, y_j, is the same under free and submerged flow. This approach proved to work very well when the gates were highly submerged, but not during initial submergence. The problem was with the energy equation on the upstream side of the structure, where assumption of the free-flow jet thickness gave the appearance of an increase in energy. We found that during initial submergence, the increase in pressure (water depth) was almost entirely offset by a decrease in jet velocity head. At higher submergence, an increase in downstream depth translated directly into an increase in upstream energy head. For a single gate opening at four discharges, we found a common relationship for the amount of energy adjustment needed, as shown in Figure 3. Combining the energy equation upstream, with the relationship in Figure 3 included, with the momentum equation

downstream results in two equations with two unknowns; the flow rate and the water depth at the vena contracta, y_2. Solution of these two equations assumes that we can estimate the water depth (and thus force) on the downstream wall of the structure based on the downstream depths (y_2 and the depth in the downstream channel), which could be problematic in some situations. Even so, if the relationship in Figure 3 proves to be consistent, it would provide a means of calibrating submerged radial gates right though the transition zone, from free to submerged flow.

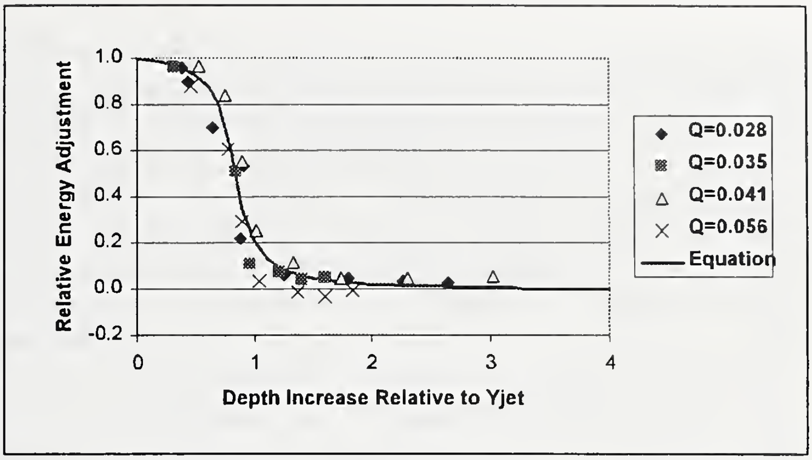


Figure 3. Energy adjustment (relative to y_2-y_{jet}) required for simple energy equation based on free flow to balance under submerged flow.

We intend to continue these studies by running tests at several gates openings, at least three. We also plan to add a J-seal, as used in the field, to the model gate to determine its effects on these relationships. We expect the J-seal to change the contraction coefficient, which makes the above relationships less general and more difficult to apply. We also plan to modify the lip of the radial gate model in the hydraulics laboratory so that the contraction coefficient remains more constant with gate angle. If this does not alter the energy loss significantly, it may provide more constant conditions for calibration. We also plan to compare this method with data from the literature.

<u>Support to Flume and Weir Design and Calibration Software</u>: The Bureau of Reclamation took our existing software for long-throated flumes (Clemmens et al. 1993) and put it in a windows environment. It is now called WinFlume (Wahl and Clemmens 1998). The program is widely used and we continue to assist the Bureau with unforeseen technical problems, enhancements, etc. We expect this to continue indefinitely, as long as the program is still widely used. A book on these flumes and weirs that includes the WinFlume software has been written and should be published in early FY02.

<u>Steep Channels/Natural Channels</u>: A prototype self-calibrating flume for sediment-laden flows was designed and installed in northern California for the California Water Quality Control Board. The objective was to develop a self-calibrating flume system and to determine its operational limitations. The design was based on estimated hydraulic behavior of a chute outlet attached to a "computable" trapezoidal long-throated flume. Two stilling wells, one on the main flume and one on the chute, provided field calibration for the chute after the main flume no longer functioned because of sediment deposits. Carrillo-Garcia (1999) subsequently conducted studies on a laboratory model of this flume, under our direction, to determine the limits of sediment handling, the best slope for the chute, and whether the calibration of the chute remains stable after the sediment fills the main flume. The sediment altered the upstream (sub-critical) stilling well as predicted. The model indicated that

the head detection in the chute will provide discharge rates with systematic errors on the order of ±5% for a given storm, compared to ±2% for the critical-depth flume. Total errors (random and systematic) for a single head measurement exceeded ±10% due to fluctuating water levels, compared to ±3% to ±5% for the critical-depth flume. The downstream stilling well in the chute (super-critical) has about the same response with and without sand, as postulated. Findings include that the midpoint of the chute is a more reliable point of depth detection than points near the downstream end of the chute. This may be related to the non-symmetric entry due to dune formation. If outside support is available, we plan to place obstructions upstream from the flume (vanes, low weir, vertical elements, etc.) to force more symmetric entry into the flume and see whether we can reduce water level fluctuations and obtain ±5% total accuracy for a single head measurement. These studies will be conducted in the hydraulics lab, and possibly other flumes in the field that have experienced similar problems (e.g., several flumes of the Salt River Project and the one in California discussed above).

Water balance and its accuracy: We have cooperated with the Lower Colorado Region of the Bureau of Reclamation on conducting water balances for various projects (e.g., Imperial and Coachella Valleys) (TWG 1994 and WST 1998). An analysis of errors was used to determine which factors contributed the most to the water balance uncertainty (Figure 4). They have requested our assistance in comparing the accuracy of (a) their decree accounting method for assigning water uses along the main stem of the Lower Colorado River (Hoover Dam to the Mexican Border) and (b) their proposed LCRAS method; however, collaborative arrangements have not been finalized (USBR 2000). They are using some of our preliminary work (developed in cooperation with others) to assist water users with defining a water balance and its associated accuracy. USGS is cooperating with them to define the accuracy of volumes for the river measurements and the major diversions and surface drains. Large diversions also have relatively accurate measurement (e.g., Central Arizona Project, California Aqueduct, All American Canal). It's the 70 or more other measurement sites plus the unmeasured return flow that pose the most problems with the water balance. We have not surveyed these sites, so we don't know what problems (opportunities) will be encountered. At this point, all we have is agreement to cooperate with USBR on this project. Our specific role in their ongoing programs is still being negotiated.

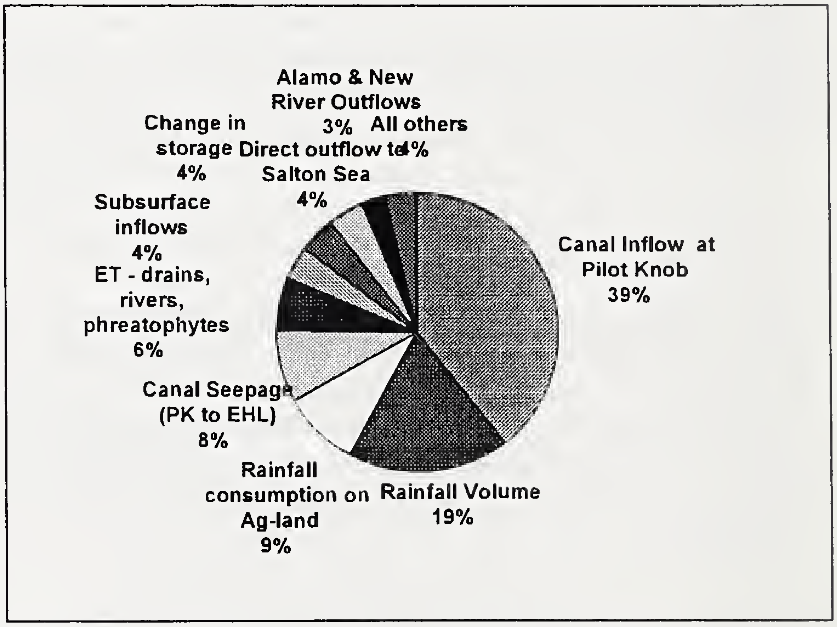


Figure 4. Distribution of error variance for estimation of net evapotranspiration of water from land area within the Imperial Valley based on a water balance. Larger wedge contribute more error to estimate. (WST 1998).

Contingencies

Other laboratory facilities could be contracted if ours are insufficient for a particular study. We have a strong track record at solving water measurement problems and expect these studies to provide useful measurement methods. In a few cases, it is not known whether or not the methods that we are testing will prove useful in the long run. If not, we will explore other user-defined measurement problems. These problems are continuously being brought to our attention by cooperators. If cooperation on the Lower Colorado River main stem does not materialize, we have several other contacts with which to pursue this research.

Collaborations

Necessary (within ARS) – None.

Necessary (external to ARS) – No cooperation is required to conduct laboratory studies. For field application we rely on the Natural Resources Conservation Service (NRCS, Tom Spofford) and the Bureau of Reclamation (USBR, Cliff Pugh and Paul Matuska).

Objective 2 - Water Control

Experimental Design

The intent of this research is to develop a complete control system for canals that is adaptable to a wide range of canal physical configurations and subject to a wide range of demands. Because there are no specific performance standards with which to judge the impact of improved water control on the performance of irrigation projects, application has been slow. Adoption is based on the desire by the water delivery agency for incremental improvement in control, improved reliability (e.g., from remote monitoring), and cost savings in labor and vehicle travel (e.g., from remote control). The proposed simulation and field studies can be used to compare various control methods and suggest which ones might be preferred in various applications as part of this control package. However, adoption of the overall control technology developed here is based on the acceptance of the users and the expectation of improved operations. For this reason, studies on the application of the technology are conducted in parallel with the more scientific controller comparison studies.

Canal control logic: Our USWCL canal control scheme consists of three component: 1) downstream water level feedback control, 2) open-loop or feedforward control (routing) of scheduled water delivery changes, and 3) flow rate control of check structures, based on flow changes from 1) and 2). We currently use a downstream feedback control scheme based on a variation of Linear Quadratic Regulator theory which allows us to develop both centralized controllers that include time delays and a series of local proportional-integral (PI) controllers (Clemmens and Schuurmans 1999). Our scheme also includes routing of scheduled water delivery changes (i.e., a modified form of gate stroking) (Bautista and Clemmens 1999). The flow controller adjusts gate position based on the gate head-discharge equations. Some testing of this system has been done through simulation (Clemmens et al. 1997, Clemmens and Wahlin 1999, and Walhlin and Clemmens 1999) under ideal conditions but also by subjecting the control system to unscheduled disturbances and system noise. Field

testing is needed to verify that the robustness and effectiveness of the system (logic and software) with given actual perturbations, system noise, and possible hardware limitations. Tuning of the feedback controllers relies on weighting coefficients in the optimization procedure that describe the tradeoff between water level errors and gate movements. To date, selection of these weighting coefficients is based on subjective judgement about controller performance. Additional simulation testing is needed to provide recommendation on these weighting coefficients. Simulation tests will be run with CanalCAD (Holly and Parrish 1992). Controllers for these and all tests discussed below will be compared with the evaluation criteria determined by the ASCE task committee on canal control algorithms (Clemmens et al. 1998). Those tests will allow to identify those controller configurations more likely to perform well under a wide range of conditions, and also controller configurations that would work best for particularly difficult situations.

We have been working with the Irrigation Training and Research Center (ITRC at Cal Poly, San Luis Obispo) on upstream control where a series of individual controllers each tries to maintain water levels upstream from a check structure. This can create oscillations in flow rates that grow in the downstream direction. ITRC has been using modified versions of our controller design programs (in MATLAB) to develop controllers for upstream control for several of their clients. We plan to conduct more general studies on upstream controller design to provide a more solid theoretical foundation. These studies are not planned for several years and details will likely be based on the results from ITRC's efforts and results of our field studies discussed below.

Our preliminary results suggest that sending control signals from one water level to more than one upstream gate improves the responsiveness of the controller. Current LQR controller design methods only consider a single canal with no branches. Thus our control scheme does not allow downstream control signals to influence gates upstream from a branch point. We have modified the standard LQR technique to design controllers for a branching canal network. We intend to test the resulting controllers through unsteady-flow simulation with SOBEK (Delft Hydraulics 2000). Initial simulation testing will be performed with ASCE test canal 1, with several downstream pools connected in the middle of the canal. If successful, we will test the branching controller with simulation of canals within the Salt River Project.

Another limitation of the proposed controllers is that they are "static," that is they are design for one set of flow conditions. If control is not robust and stable over the full range of conditions, the controller must be tuned for different ranges of conditions (i.e., gain scheduling). Model Predictive Control (MPC) has the advantage that the controller is tuned for the current conditions, however this requires on-line optimization. With the current state-of-the-art in canal control, we are not comfortable with on-line optimization. However, we will test MPC for the branching canal tests discussed above.

<u>Canal automation software</u>: The research unit has developed a canal automation software system that controls canals remotely through a commercial Supervisory Control and Data Acquisition (SCADA) System using commercially available hardware in the Windows NT environment. We have entered into a Cooperative Research and Development Agreement with Automata Inc. to develop a canal automation product line. Our automation software runs in parallel with the SCADA software (Fix Dynamics, by Intellution Inc.) and accesses the SCADA database to determine the

current status and to cause actions to take place (e.g., change in gate position). Automata's remote terminal unit (RTU) provides sensing and control functions. Preliminary field testing in the fall of 1999 was successful (Strand et al. 1999). Figure 5 shows a sample SCADA screen with water level output. We are in the process of adding fail-safe routines so that the controller does not act inappropriately when data are missing or sensors malfunction (as for WM-5 in Figure 5). More rigorous field testing of this system will start in mid 2001 and continue through at least 2002. The system should be turned over to the CRADA partner within FY02. Continued software upgrading is planned through FY03. We plan to support the CRADA partner's efforts through 2004.

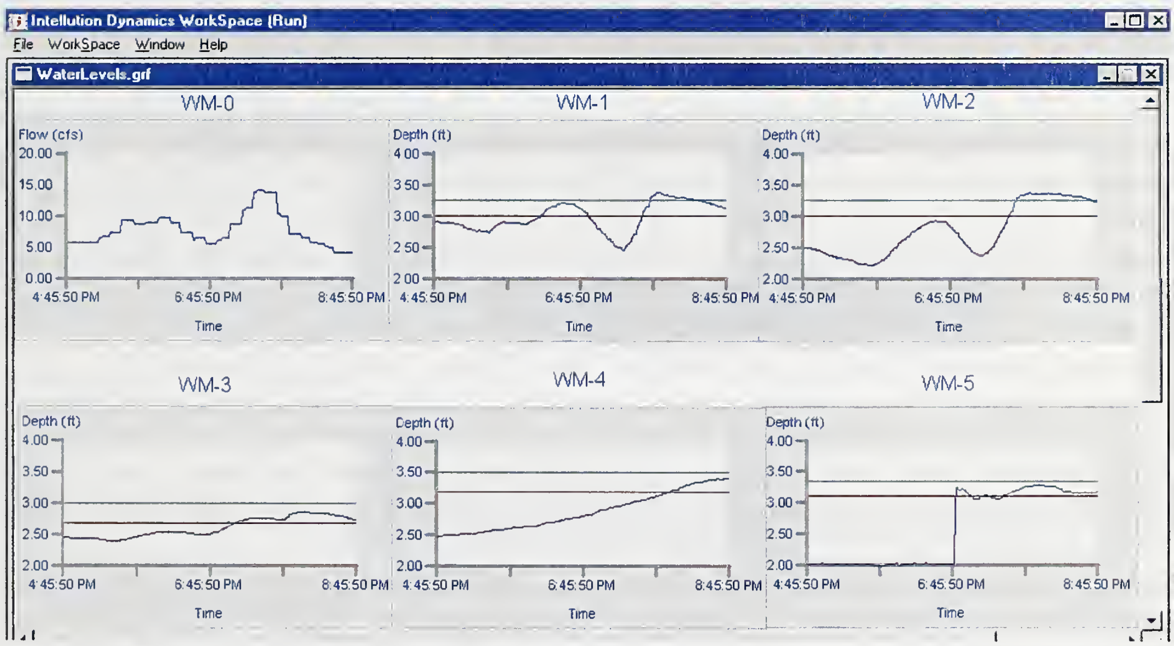


Figure 5. FIX SCADA screen showing results of test on October 19,1999. Red lines are water level set points and green lines are overflow weirs.

Field testing on WM canal: The field testing of the canal automation system will be performed on the WM canal of the Maricopa Stanfield Irrigation and Drainage District (MSIDD), which has a 2.5 m^3/s capacity. This canal is at one extreme of hydraulic conditions (small, steep, with little storage). Groundwater wells are available that pump water directly into the canal (roughly 0.1 m^3/s). These can be turned off or on to simulate demand changes. The district allows us to operate the canal, either manually or automatically, while their normal deliveries are taking place. The main focus will be on downstream water-level feedback control methods, both centralized and local. We will start by testing a series of simple PI controllers on only the upstream half of the canal. Initially, we will test only downstream feedback control with pseudo-demand changes, generated by turning pumps on or off. Then we will route these pseudo-demand changes down the canal with our routing program as if they were scheduled, and with the feedback system still on. Performance will be measured with the ASCE Task Comimittee performancee indicators under a variety of flow conditions. If successful, we will expand to control of the entire canal and eventually route the actual demand changes down the canal and operate it automatically during normal delivery changes. We also will test downstream controllers that include lag-time predictions and the fully centralized

LQR controllers and several intermediate controllers as discussed in Clemmens and Wahlin (1999). We will attempt to run these various controllers under different flow and demand conditions. Further testing on canals with different properties, for example where backwater effects as significant, is planed for later stages of this project. Possible sites include lateral E12 at MSIDD and one of the lateral off the East Highline Canal in the Imperial Valley. However, we will not pursue these sites (or collaboration at Imperial) until testing is competed at MSIDD and the system can be demonstrated.

SRP pilot study: We are currently completing studies on one of the larger canals of the Salt River Project (SRP) to test the feasibility of applying this technology within SRP's operating environment. We are also using this cooperation to test the acceptability of such control methods to their operating staff. We conducted simulation studies with the unsteady-flow simulation software program Mike 11 (DHI 1992) to demonstrate the technical feasibility of the feedback and feedforward (routing) scheme (Clemmens et al. 1997). Example simulation results are shown in Figure 6. We have also examined various practical issues, including: (1) comparison of water level deviations for real demand conditions under (a) simulated automation and (b) actual manual control (Brouwer 1997); (2) use of identification techniques to estimate canal hydraulic parameters for controller design (Silvis 1997 & Silvis et al. 1998), (3) analysis of the limitations imposed by the limit storage at the diversion structure which supplies water to the canal (This suggested the need to control a section of the river between the storage and diversion dams (Visser 1998), and the need for control of branching systems.); (4) analysis of start-up procedures for the feedback system (Bautista et al. 1999); (5) analysis of performance for alternative controller designs (Wahlin and Clemmens 1999); and (6) calibration of the head-discharge relationship for radial gates (Tel, 2000). Several of these studies were conducted in collaboration with graduate students from Delft Technical University.

We are currently testing the routing procedures in cooperation with Salt River Project by comparing the program's and the operator's schedules of flow changes. The objective is to identify possible problems with the control algorithm given the range of operational conditions experienced in the real canal. Furthermore, these tests should help reassure operators that the computed schedules are reasonable and would not endanger the canal. We plan to complete these tests by September 2001. Depending on the outcome of these tests, we propose to conduct off-line tests in FY02. With these tests, we plan to demonstrate that the proposed open-loop control algorithm can improve water level control relative to the heuristic approach currently employed by the operators. If the off-line testing is successful, we will request SRP's approval to automate the execution of the computed schedules, in real time. This will require our routing software to be implemented within SRP's computer operating systems and, thus, will serve to identify practical implementation problems. If this is successful, we will propose implementation of the feedback control system. (SRP is already implementing their own flow-control function).

Dual-acting controlled leak: For situations where communication and remote power are not available, mechanical/hydraulic automatic control devices are needed. The research unit developed such devices in the late 1980s and proposes to do additional development and testing of these devices (Clemmens and Replogle 1987). The DACL controllers have two limitations: (1) the two values have to be carefully adjusted relative to one another and (2) the gate controls were done with very large counter balanced floats on radial gates. We propose to develop a single valve with the required dual action and to use inflatable bladders to do away with the current float/ counterweight system. This will make such devices much more easy to retrofit to existing gate structures, including sluice gates. Two prototype values have been built, but not yet tested under operational conditions. Several bladder systems have been tried, but finding the right combination of materials has proved challenging.

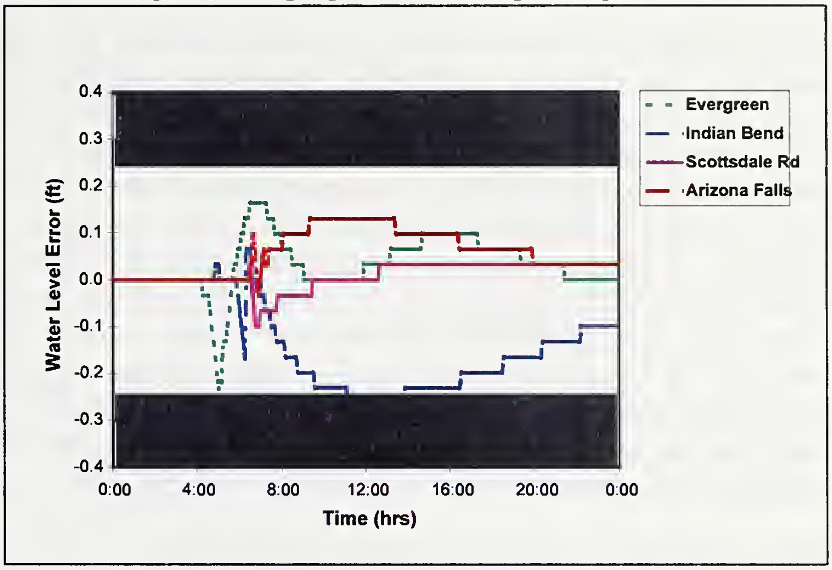


Figure 6. Difference between actual and target forebay water level under simulated automated control in four Upper Arizona Canal pools for Test 5 from SRP Canal Automation Pilot Project. (Clemmens et al. 1997). (Inside band is acceptable or "green" zone, shaded is "yellow warning zone, outside figure is "red" zone).

Contingencies

Field studies rely on cooperation with irrigation districts and a CRADA partner to test these systems in real time on operating canals. If the current collaborations were to end, new collaborators would be found to continue the research. We are just ending a canal automation research project with the Salt River Project. Implementation was postponed, but they are a potential alternative site if cooperation with MSIDD doesn't work out. We also have had close cooperation with Imperial Irrigation district in the past, so they are another potential candidate for cooperation. If the controller design methods being used/developed do not work for a particular canal, there are a number of other control methods that can be used (e.g.. Model Predictive Control). Some of these other controllers will be examined through simulation so that we gain familiarity with them.

Collaborations

Necessary (within ARS) – None.

Necessary (external to ARS) – Maricopa Stanfield Irrigation and Drainage District (Gary Sloan), Salt River Project (Bob Gooch), Automata, Inc. (Lenny Feuer), Irrigation Training and Research Center (Charles Burt), and USBR Water Resources Research Laboratory (Cliff Pugh).

Physical and Human Resources:

This research project includes three category I research scientists (1.79 SY), two category III research scientists (1.4 FTE), and an engineering technician (1.0 FTE, GS-9 on temporary term appointment). We will hire additional temporary personnel as needed. This labor force is sufficient to carry out the needed work.

The research is conducted at the U.S. Water Conservation Lab which has office and laboratory space available for a wide variety of studies. Employees utilize the 372 m^2 hydraulics lab for small-scale studies on flow measurement and canal automation. However, these are currently utilized primarily for another project. The hydraulics lab includes 5 pumps (30, 20, 20, 15 and 15 Hp), two large sumps, a constant head tank, 25 ton hanging weigh tank, 15.2 m long glass lined flume (1.2 m wide by 0.6 m high), and a 760 mm diameter concrete pipe section 12 m long. The system has a capacity of 450 l/s, depending on which experimental apparatus is being used. The weight tank system can measure flow rates to within 0.1%. A soils lab is available to conduct soil particle size analysis. An electronics shop is available for development and repair of electronic instruments as needed. Water chemistry labs, primarily associated with other projects, are available for testing soil and water for constituents if needed. The laboratory has an internet connection (T1 line), a local area network, and numerous personal computers for the staff. Much of the research of this group is conducted with customers and cooperators on their sites to assure relevance.

MILESTONES AND EXPECTED OUTCOMES

Expected outcomes include: (1) improved water measurement devices, (2) new canal automation technology, and (3) improved water use assessment methods and performance indicators.

Milestone Timeline

Research Component	end of year 1	end of year 2	end of year 3	end of year 4	end of year 5
Water Measurement and Accounting	Lab study on flow conditioning for pipes/culverts completed (Replogle)	Lab study on debris-shedding propeller meter completed (Replogle)	Field studies on surface-velocity-based method completed (Replogle)	Lab study on high sediment load flume completed (Replogle)	
		Laboratory studies on submerged radial gates completed (Clemmens)	Verification of radial gate calibration method completed (Clemmens)		Field study on water balance accuracy completed (Clemmens)
Water Control	Initial version of canal automation system turned over to CRADA partner (Clemmens)	Improved interface for canal automation system provided to CRADA partner (Clemmens/Bautista)	Final version of canal automation technology given to CRADA partner (Clemmens)		New DACL control system developed and lab testing completed (Replogle)
		Field studies of canal automation on steep canal (WM at MSIDD) completed (Clemmens)	Field application of feedforward routing method completed (Bautista)		Field studies of canal automation on canal with mild slope complete (Clemmens)
	Feedback control method for branching canals developed and simulation testing completed (Clemmens)	Simulation testing of Model Predictive Control for branching canal completed (Clemmens)		Upstream control method developed and simulation testing completed (Clemmens)	

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ASSESSMENT AND CONTROL OF PATHOGENS IN MUNICIPAL WASTEWATER USED FOR IRRIGATION TO PROTECT CROPS AND GROUNDWATER

Norma L. Duran, Microbiologist

PROJECT SUMMARY

Population growth and water shortages will increase the need to use treated wastewater effluent for irrigation, particularly in areas where fresh water resources are limited. However, there are serious concerns about the transmission of pathogens and toxic chemicals from municipal and animal wastewater to agricultural land and crops and thus to human food and to groundwater. An increase in foodborne disease in the US has been attributed in part to the transmission of pathogens in the water used for irrigation of edible crops. Furthermore, there is limited knowledge on the long-term effects of irrigation with sewage effluent on soil and underlying groundwater. Thus, the aim of this research project is to assess the microbiological safety of wastewater irrigation of food crops and potential environmental hazards in order to protect the public health and our future groundwater resources. Molecular biology techniques will be used to evaluate pathogen survival, regrowth, and transport in vegetated and non-vegetated soil columns, water distribution systems, and field sites with a long history of wastewater application for crop irrigation. Studies will determine the movement of pathogens through the soil column as well as the factors affecting their survival and transport. This could lead to the development of management strategies that would minimize the introduction of pathogens into the environment and thus reduce the risk to human health.

OBJECTIVES

1. Determine the fate and transport of pathogens present in treated sewage using vegetated (grass and alfalfa) and non-vegetated soil columns irrigated at various efficiencies or flooded to simulate artificial groundwater recharge conditions with chlorinated secondary sewage effluent. The columns will also be used to determine the fate of organic compounds, such as pharmaceuticals and pharmaceutically active chemicals and disinfection by products under a companion project under National Program 201, Water Quality and Management (Wastewater Irrigation and Groundwater Recharge).

2. Determine if wastewater irrigation has an effect on groundwater quality by analyzing upper groundwater samples below agricultural fields, urban irrigated areas (golf courses, parks, landscaping), and/or groundwater recharge areas with a long history of municipal wastewater application for emerging microbial pathogens including but not limited to *Escherichia coli* O157:H7, *Salmonella*, and *Campylobacter*. The samples will also be analyzed for pharmaceuticals and other chemicals under a companion project.

3. Determine if bacterial pathogens present in treated sewage can regrow in conveyance systems used to transport wastewater to fields for irrigation of fresh fruits and vegetables and conduct laboratory studies using a model system to determine the physical and chemical factors that promote/inhibit pathogen regrowth so that cost effective prevention strategies can be developed.

NEED FOR RESEARCH

Description of the problem to be solved

Increasing populations, finite water resources and increasingly stringent treatment requirements for discharge of sewage effluent into surface water is increasing the need for water reuse practices in

the United States. However, due to recent foodborne outbreaks, public concern about the potential human health risks and environmental consequences of water reuse in agriculture is increasing. Thus, research is needed to increase our current knowledge on the long-term effects of wastewater irrigation on food, soil and underlying groundwater. In addition, the potential for pathogen regrowth in conveyance systems used to transport treated wastewater over long distances to the irrigated areas also deserves attention. Furthermore, proper assessment of water reuse practices will require microbial detection methods that are fast, sensitive and specific for pathogens of concern. Addressing these research needs will help assess the environmental and public health risks associated with wastewater irrigation so that future problems of food, soil and groundwater contamination can be anticipated or avoided.

Relevance to ARS National Program Action Plan

The research directly addresses national and global problems dealing with safety of food produced in fields that have been irrigated with treated sewage effluent or with effluent contaminated water. This project falls under National Program 108, Food Safety, Microbial Pathogens Component. The reduction of microbial pathogens in food products also relates to reducing environmental contamination from animal (and human) waste. This project is related to objective 1.6.1.1 "Identify sources and reservoirs of pathogens relative to on-farm and environmental situations" by determining the fate of pathogens in wastewater applied as irrigation to crops.

Potential benefits expected from attaining objectives

Benefits from attaining the objectives include safe use of sewage effluents for irrigation from the standpoint of food safety and groundwater protection. Water reuse will be more common and the practices will be safer for public health.

Anticipated products of the research

Anticipated products of the research include (1) improved techniques of sewage treatment and system management for safe and sustainable water reuse with minimum adverse health effects and in environmentally acceptable ways, and (2) new guidelines for irrigation with wastewater to protect groundwater and surface water quality and for control measures of pathogen regrowth in water distribution systems.

Customers of the research and their involvement

Customers of the research include the public, farmers and farm workers, water planners and managers, government regulators, consulting engineers, water districts and municipalities, wastewater treatment plant operators and water managers.

SCIENTIFIC BACKGROUND

Municipal sewage effluent is becoming an increasingly significant water supply for irrigated agriculture all over the world and could help reduce groundwater pumping as well as conserve water in arid areas. In the United States, increasing demands on the nation's water supplies have led to

reuse of wastewater following treatment (largely for nonpotable uses such as irrigation) particularly in areas with limited water resources. For example, in the Northern Monterey County portion of the Salinas Valley, over 11,850 acres are being irrigated with tertiary wastewater effluent for the production of various crops including artichokes, head lettuce, celery, broccoli, and cauliflower (Israel, 2000). Many of these crops are washed and bagged for raw consumption in many parts of the country. In Bakersfield, California, approximately 5,100 acres of corn, alfalfa, cotton, barley and sugar beets are being irrigated with more than 16.9 million gallons per day of primary and secondary wastewater effluents. In Tallahassee, Florida, approximately 18 million gallons per day of secondary effluent are being pumped through 8.5 miles of pipeline to irrigate 1,729 acres of food crops by spray irrigation. Although the use of wastewater for irrigation is increasing, the risks to public health and the long-term effects on groundwater quality are largely unknown and deserve attention.

New foodborne pathogens are emerging in the U.S. and irrigation water has been identified as a source of contamination (Mead, 1997). During 1999, thirty three percent of the foodborne outbreaks reported were caused by fruits and vegetables such as apple cider, cantaloupe, lettuce and alfalfa sprouts (Prier and Solnick, 2000) that had been irrigated with wastewater or water that had become contaminated. Recent outbreaks of foodborne illness have been associated with produce, including *E. coli* O157:H7 in lettuce (Hilborn et al., 1999) and *Cyclospora* in imported raspberries. These outbreaks together with the increase in wastewater irrigation practices have raised public concern regarding the safety of fresh fruits and vegetables (Meng and Doyle, 1997). In addition, there is growing concern about the long-term effects of wastewater irrigation on groundwater quality. Groundwater contamination with bacterial pathogens can occur by several routes including leaking sewer lines and land discharge by passage through soils and fissures. Groundwater supplies half of the nation's drinking water and accounts for 37% of agricultural irrigation supporting many billions of dollars worth of food production (USEPA, 1999). Thus, it is important to protect our groundwater resources from possible contamination through wastewater irrigation practices and artificial recharge of groundwater. This project will evaluate the safety of these practices to reduce human health risks and ensure groundwater quality.

Municipal wastewater contains a variety of viral and bacterial pathogens (Table 1) that have been excreted in the feces of infected individuals. Some of the most common pathogens found in raw wastewater include *Salmonella* (Asano, 1998), *Mycobacterium*, *Escherichia coli* (Tsai et al., 1993; Grant et al., 1996), and *Campylobacter jejuni* (Jones, 2001). Hence, the use of reclaimed water for crop irrigation requires pretreatment followed by disinfection in order to minimize the risk of disease transmission. However, wastewater treatment only reduces the amounts of pathogens in finished water and does not eradicate the disease agent (Asano, 1998). For example, it has been reported that even though *Campylobacter* can be reduced during treatment to 99.9%, there are 10^{10} *Campylobacters* left in the treated effluent (Arimi et al., 1988). This is of great concern since the infective dose of *Campylobacter* in humans is low (~500 cells). In fact, *Campylobacter* infections exceed those of previously most commonly reported enteric bacterial infections in the U.S. and it is the number one cause of all domestic foodborne illness (Okum, 2000). In addition, *Campylobacters* have been found in vegetables such as spinach, lettuce, and parsley (Kumar et al., 2001). Thus, the potential transmission of infectious disease by pathogenic agents is the most common concern associated with nonpotable reuse of treated municipal wastewater.

Table 1. Some pathogens of concern in municipal wastewater and sewage sludge (U.S. EPA, 1989)

Bacteria	Viruses	Protozoa
Salmonella spp.	Hepatitis A	*Cryptosporidium*
Shigella spp.	Rotavirus	*Giardia lamblia*
Campylobacter jejuni	Norwalk Agents	*Entamoeba histolytica*
Escherichia coli	Coxsackievirus	*Balantidium coli*
Yersenia	Echovirus	*Taxoplasma gondii*
Vibrio cholerae	Reovirus	

Wastewater containing pathogens can contaminate crops directly by contact during irrigation or indirectly as a result of soil contact. Therefore, it is essential that we understand the factors affecting the quality of irrigation water as it leaves the treatment plant and during its transport to the fields. Current guidelines for unrestricted irrigation with effluents apply only to the effluent as it is discharged from the sewage treatment plant and not as it leaves the distribution system. Studies have shown that although the water may leave the treatment plant with a uniform level of quality, it has the potential to exhibit a highly variable pattern of water age and quality throughout a distribution system (LeChevallier et al., 1996; Volk et al., 1999). Clogging problems due to microbial growth have been reported for sprinkler and drip irrigation systems using reclaimed wastewater (Asano, 1998). Long residence times of water in a distribution system can have the following negative effects; loss of disinfectant residual, formation of disinfection by-products, growth of biofilm colonies along pipe walls, and the protection and subsequent release of nuisance and pathogenic microorganisms from the biofilm over time (Volk et al., 1999). Thus, there is growing concern about the potential for pathogen regrowth in the water distribution systems particularly where the effluent is transported over long distances to the irrigated areas (mostly with pipelines). A better understanding of the physical, chemical, and biological activities that occur in distribution systems will help minimize the health risks associated with the reuse of wastewater in food production (Raucher, 1996). The USDA's food safety initiative calls for the development of cost effective prevention strategies to reduce the incidence of foodborne illness. Hence, part of this project will involve the study of operational factors affecting pathogen regrowth in conveyance systems to ensure that the quality of reclaimed water is not degraded prior to its use.

Proper assessment of water quality and reuse practices requires microbial detection methods that are fast, sensitive and specific for pathogens of concern since indicator microorganism are not adequate predictors of treatment resistant pathogens. Chlorination is the disinfectant most commonly used in wastewater treatment. It is now known that there are chlorine resistant microorganisms such as viruses (Metcalf et al., 1995) and protozoans (Steiner et al., 1997) that are not killed or inactivated during disinfection. In addition, chlorination can elicit a nutrient starvation and a reversible non-culturable (VBNC) state of coliform bacteria and other pathogens (Rockabrand et al., 1999). This aggravates the limitations posed by conventional cultivation techniques since VBNC pathogens will not grow in laboratory media. Therefore, culture-based methods underestimate the fecal coliform content and do not possess the sensitivity required to detect low numbers of pathogens that exist in the presence of high numbers of indigenous microorganisms in complex environmental samples such as water, manure or biofilms. Also, it is known that less than 1% of the bacterial population

from oligotrophic systems can be cultivated in the laboratory. Staley and Konopka (1985) have described this phenomenon as "the great plate count anomaly". Bacterial pathogens that are not destroyed during treatment have the potential to multiply and become infective when the conditions become favorable and should not go undetected.

Recent advances in recombinant DNA technology provide new tools to rapidly detect specific pathogens in the environment and thus, overcome the limitations of culture-based methods (Metcalf et al., 1995; Relman, 1998). Molecular techniques allow the direct identification of targeted foodborne pathogens such as *Escherichia coli* O157:H7 (Meng and Doyle, 1997) from environmental samples and can detect bacteria that are in a viable but non-culturable (VBNC) state. These methods have superior sensitivity to that of cell cultivation. PCR methods have the ability to detect up to one bacterial cell in a sample, they can detect the VBNC bacteria, and when amplifying mRNA (by an RNA PCR), they can distinguish live cells from dead cells. However, the ability to detect specific pathogens of concern from environmental samples presents a challenge to environmental microbiologists because of low DNA recovery rates and the presence of inhibitory substances such as humic acids in environmental matrices. The lead scientist has successfully studied environmental microbial communities using PCR and gene probes. In a study conducted in collaboration with New Mexico State University and the U.S. Environmental Protection Agency (ORD/NRMRL/SPRD), shifts in microbial communities were detected in samples taken from a contaminated aquifer. The data demonstrated that the aquifer contained a diverse microbial community, which had not been previously identified using conventional cultivation methods (Duran, submitted). Two of the organisms that were identified by molecular methods were later isolated in pure culture. However, the organism identified as archaeabacteria could not grow on laboratory media possibly because this is a novel organism and not much is known about its metabolism to allow synthesis of proper growth media. Another possible explanation is that this organism is a synthrophic archeabacteria meaning that it cannot grow without the association of other bacteria and thereby cannot be isolated nor identified by culture-based techniques. The lead scientist also conducted a project in collaboration with the U.S. Environmental Protection Agency and the U.S. Department of Agriculture, Forest Service, to study the effectiveness of a restored riparian buffer zone to attenuate nitrogen inputs from agricultural practices using molecular methodology. Soil samples were collected from the restoration site and DNA was extracted and purified. Denitrifying bacteria were then identified through the detection of the *nir*S and *nir*U type nitrite reductase genes using the PCR technique (Duran, 2001). Thus, once the challenges of DNA isolation and recovery are overcome, PCR techniques and gene probe methodologies can provide a powerful and sensitive option for detection of microorganisms in environmental samples and will be the method of choice for this project.

Other related CRIS projects:

A CRIS search of active projects on animal manure and wastewater irrigation identified 22 projects, of which two are from this research unit. CRIS projects of relevance to this research include a project by the Western Regional Research Center in Albany, CA (#5325-42-000-023-00D) dealing with treatment of animal manure to prevent pathogen transmission and to gain a better understanding of pathogen ecology in agricultural settings. Another related project is being conducted by the U.S. Meat Animal Research Center in Clay Center, NE (#5438-42000-006-00D) dealing with the prevention of zoonotic pathogen transmission from animal manure to human food. Both of these

research projects are similar to my proposed research in that they use a molecular biology approach for the detection and identification of specific pathogens including *Campylobacter* from environmental samples; however, they are addressing potential contamination through animal waste rather than municipal waste used for agriculture. Another related project is being conducted by ARS in Athens, Georgia (#6612-13610-002-09R, "Subsurface transport of *Cryptosporidium* and *Giardia* from grazing lands to drinking water supplies") to help understand the transport of pathogens in the subsurface to a stream, however it uses polystyrene microsphere in place of the pathogens. A project by the University of California, Riverside, (CRIS #5310-42000-001-02S) includes the fate and transport of pathogenic microorganisms in surface water, groundwater and the atmosphere from animal waste (beef or poultry) products. Also, a CRIS project (5344-42000-013-00D) is being conducted in my research unit as a companion study to my proposed project. This study addresses the fate and transport of organic chemical present in wastewater used for irrigation including endocrine disruptors. In addition, CRIS #4344-42000-13-01S by Arizona State University is being conducted within my laboratory to see if pharmaceutically-active compounds present in wastewater can pose a threat to groundwater quality.

Several CSREES projects were identified that are considered complimentary to the research proposed herein. However, some of these projects may no longer be active. CSREES # 96-35102-3839 "Role of subsurface drainage in transport of *Cryptosporidium parvum* oocysts" conducted by Cornell University, Ithaca, NY addresses the transport of *Cryptosporidium* in the subsurface through preferential flow paths in the soil. CSREES #ARZT-319650-G-21-512 "Role of irrigation water in contamination of imported and domestic fresh food" is a project using wastewater irrigation conducted by the University of Arizona, Tucson. The irrigation waters from canals used for crop irrigation were assessed for the presence of pathogens, however the impact of irrigation on groundwater quality was not addressed. CSREES #PEN03571 "Wastewater irrigated forests for timber and wildlife" conducted by Pennsylvania State University uses municipal wastewater as irrigation to study abundance and distribution of plant communities.

APPROACH AND PROCEDURES

Experimental Design

Objective 1 - Soil Column Studies

The main purpose of this study is to assess the safety of water reuse practices, mostly for urban and agricultural irrigation, so that the risk to human health and groundwater contamination are minimized. Ten soil columns in 8 ft long x 1 ft wide stainless steel pipes were set up in a greenhouse at the U.S. Water Conservation Laboratory to study the movement of pathogens in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and recharge and irrigation with Colorado River water. The columns were filled with a sandy loam from the McMicken Flood Control reservoir northwest of the City of Surprise. This is a desert soil in the Mohall-Laveen Association that has had no agricultural use. The hydraulic conductivity of the soil was determined with a laboratory permeameter test as 280 mm/day, using a disturbed sample. To avoid particle segregation, the soil was placed in the columns in air-dry condition followed by compaction with a rod. The effects of different infiltration rates and recharge conditions on the survival and transport of pathogens and effects on groundwater quality will be determined in the soil

columns. Because of space and other physical limitations, only ten columns could be set up. Thus, the schedule in Table 2 was developed so as to include as many different treatments as possible, including different crop and soil conditions (legume, non-legume, and bare soil), different modes of water application (irrigation and recharge), different irrigation efficiencies, and different sources of water (effluent and Colorado River water). Initially, there will be no replications since variability issues theoretically do not exist in these engineered columns. In addition, this orientation-type study will permit us to maximize the use of the columns and obtain the maximum information that will allow the observation of trends, particularly with regard to the different irrigation efficiencies, which have not been previously published. However, depending on the results, replicate treatments may be used in the future to firm up some of the conclusions. The irrigation efficiencies in Table 2 will be determined as ET divided by amount of water applied and expressed as a percentage. ET will be calculated from the weight loss of the column as measured with load cells on which the columns are resting. Estimates of irrigation efficiency will also be obtained from EC values of irrigation water and leachate.

Table 2. Schedule of irrigation and recharge studies for soil columns in the greenhouse

Column #	Cover	Irrigation Efficiency	Water Source
1	grass	50%	Effluent
2	grass	70%	Effluent
3	grass	90%	Effluent
4	alfalfa	50%	Effluent
5	alfalfa	70%	Effluent
6	alfalfa	90%	Effluent
7	bare soil	70%	Effluent
8	grass	70%	Colorado River Water
9	bare soil	recharge mode	Effluent
10	bare soil	recharge mode	Colorado River Water

The sewage effluent to be used in the column studies will be representative of typical wastewater treatment for non-potable uses such as irrigation of crops, parks, playgrounds, golf courses and residential yards. The effluent should have, as a minimum, primary and secondary treatment followed by chlorination. Also the effluent should primarily be of residential origin with not much industrial input. The Goodyear and Tolleson wastewater treatment plants in Arizona meet these requirements. However, since the soil columns will also be used in a companion project to study the transport of organic chemicals including pharmaceuticals, sewage effluents from both wastewater treatment plants were collected and sent to Dr. David L. Sedlak's laboratory of the Civil and Environmental Engineering Department at the University of California at Berkeley for analysis of pharmaceuticals. The results demonstrated that very low concentrations of pharmaceuticals were present in the Goodyear effluent while the Tolleson effluent contained concentrations that were more in line with typical values (Table 3). Hence, sewage effluent from the Tolleson wastewater treatment plant will be used in the column studies. Colorado River water will also be used as a comparison to wastewater irrigation.

Table 3. Concentrations of selected pharmaceuticals in the Goodyear and Tolleson effluent

Pharmaceuticals	Concentrations	
	Goodyear	Tolleson
Ibuprofen	17 ng/L	247 ng/L
Naproxen	22 ng/L	699 ng/L
Indomethacine	<3 ng/L	55 ng/L
Metoprolol	20 ng/L	133 ng/L

The sewage effluent and drainage water from the columns will be analyzed for selected pathogens including but not limited to *E. coli* O157:H7, *Campylobacter*, and *Salmonella*. Once we determine which pathogens present the greatest risk to groundwater, the columns will be sampled at different depths including the root zone of vegetated columns to obtain detailed pathogen transport data. All microbiological analysis will be carried out by polymerase chain reaction (PCR) technology and/or gene probe methodology using published detection sequences specific for the pathogens of concern.

Sampling of sewage effluent and DNA extraction will be carried out using a protocol by Smalla (1995) with minor modifications. All water samples will be concentrated in Sterivex filters (Millipore) and DNA extraction will take place inside the filters followed by ethanol precipitation. Preliminary results for wastewater sampling and DNA recovery have resulted in good yield of high quality DNA as determined by spectral analysis (Table 4). DNA extraction from soil and root samples will be carried out using a modified bead-mill procedure (More et al., 1994; Van Elsas and Smalla, 1995). All community DNA will be purified using a glass milk purification kit (Bio 101) and will be subjected to PCR tests to assess the presence of specific pathogens using published primer sequences (Table 5). Real-time PCR will be performed using a GeneAmp 5700 (Perkin Elmer) and should allow for the enumeration of pathogens originally present in the sample. This information together with the infective dose (Kowal, 1985) of the organisms can be valuable for determining if the pathogens are present in significant numbers to cause a human health risk. All procedures will be optimized in the laboratory using DNA from stock organisms that will be purchased from the American Type Culture Collection (ATCC). Positive and negative controls will be included in each sample analysis. The positive control will contain DNA from the ATCC stock organisms and the negative control will contain distilled water. General PCR practices will be followed to avoid contamination of the samples and non-specific amplification (Griffin and Griffin, 1994). Separate areas in the laboratory will be devoted to sample processing, nucleic acid purification, PCR mixture preparation, and examination of PCR products. All laboratory surfaces and equipment will be cleaned with 90% ethanol and/or 10% bleach. In addition, aerosol filter pipette tips will be used. If non-specific amplifications (false positives) are observed through the dissociation profiles or upon agarose gel electrophoresis, the AmpErase uracil-N-glycosylase (UNG) (Applied Biosystems) will be used to remove previously amplified copies and prevent reamplification of carryover PCR products. When gene probes are used, the Southern blot procedure will be followed as detailed in Ausubel et al. (1999). Southern blotting is a technique for identifying a DNA sequence by providing a chemiluminescent complimentary probe that binds to it. Thus, hybridization and colorimetric detection of bound probe will be performed using the DIG Nucleic Acid Detection Kit (Roche).

Table 4. DNA yield from wastewater effluent samples and soil column drainage	
Sample	DNA concentration
Tolleson effluent	58.5 μg/ml
Sewage effluent from top of the column	24.9 μg/ml
Sewage effluent from bottom of the column	34.9 μg/ml

Table 5. List of pathogens and their PCR-target sites

Pathogens	PCR-Target sites	References
E. coli O157:H7	Shiga-like toxin gene (*slt*I-*slt*II)	Gannon et al., 1997
	*eae*A gene	Oberst et al., 1998
Campylobacter jejuni	Flagellin gene (*fla*A-*fla*B)	Kirk and Rowe, 1994
16S rRNA gene	Waage et al., 1999	
Salmonella	phoP, H-li and Hin genes	Way et al., 1993 Wang, et al., 1997

Contingencies

This research relies on cooperation with the City of Tolleson to obtain wastewater. If this falls through, another source of wastewater can easily be found. Arrangements were made with the Central Arizona Water Conservation District to obtain Colorado River water from the Central Arizona Project (CAP) Aqueduct at a point where the canal has 100% Colorado River water through a companion project, if this falls through, we can collect water from the Colorado River or change to a different water source.

Collaborations

Necessary (within ARS); collaboration with research hydraulic engineer, Herman Bouwer, at the U.S. Water Conservation Laboratory is required for the set up and operation of the columns, as described in his Project Plan under National Program 201.

Objective 2 - Field Studies

Studies to investigate the potential detrimental effects of animal wastes released into the environment on groundwater quality have recently been conducted. However, the effects of municipal wastewater irrigation on underlying groundwater quality have not been addressed and deserve attention. For example, Cho and Kim (2000) have studied the effects of livestock wastewater on underlying groundwater quality and found that the increase in bacterial-community diversity in the contaminated aquifer was probably due to the infiltration of livestock wastewater.

Also, Chee-Sanford et al. (2001) examined two swine farm lagoons and found the presence of tetracycline resistance determinants in the underlying groundwater, which could be detected as far as 250 meters downstream from the lagoons. Thus, the purpose of this objective will be to evaluate laboratory-derived results under natural field conditions in order to better understand microbial transport behavior in the subsurface and evaluate the effects of wastewater irrigation on groundwater quality. It is imperative that we combine both laboratory and field studies because although column studies provide a greater degree of control, they cannot account for the many factors that control microbial mobility in situ such as hydrological characteristics of the aquifer, preferential flow, predation, motility, lysis, changes in cell size in response to alterations in nutrient conditions, spore formation, and attachment to soil surfaces. Sites will be selected on the basis of depth to groundwater (preferably shallow), availability of wells that pump primarily upper groundwater, and cooperation with farmers, irrigation districts, and municipalities. Two potential field sites in Phoenix, Arizona, are currently being evaluated based on the criteria described above. One of these sites is the Buckeye Irrigation District, which uses approximately 30,000 acre-feet per year of treated sewage effluent produced by the 91st Avenue Wastewater Treatment Plant for the irrigation of crops. The other site is the Roosevelt Irrigation District, which uses 33,000 acre-feet per year of treated sewage effluent produced by the 23rd Avenue Wastewater Treatment Plant for the irrigation of edible food crops such as vegetables and melons. Experiments will be designed to determine if there are significant differences in the microbiological quality of groundwater at existing groundwater recharge sites and below agricultural fields where wastewater irrigation has been conducted over long periods of time compared to selected control sites. Monitoring wells previously installed by the USGS to sample for pesticides and industrial chemicals will be evaluated for the use of microbiological sampling. At least two to three well volumes will be flushed prior to collecting groundwater samples (in duplicate) for microbiological and geochemical analysis. Care will be taken to conserve the integrity of the samples collected and to prevent microbial contamination during sampling. Autoclaved glass bottles will be used and filled all the way to the top to avoid any headspace. The groundwater samples will be chilled immediately after collection and will be transported to the laboratory on ice where they will undergo analysis for microbial pathogens using procedures described for sewage effluent in objective 1. Geochemical measurements will also be conducted. In the event that we require concentration of bacteria prior to nucleic acid analyses, we will use a hollow-fiber, tangential-flow filtration system described by Kuwabara and Harvey (1990).

Contingencies

Arrangements will be made with irrigation districts, municipalities, and landowners to permit sampling water from existing wells. There is enough interest in the effect of sewage irrigation on groundwater quality that adequate cooperation should not be a problem.

Collaboration

- Necessary (within ARS); collaboration with research hydraulic engineer, Herman Bouwer, at the U.S. Water Conservation Laboratory is required for site characterization and selection of field sites.

- Necessary (external to ARS); collaboration with the U.S. Geological Survey (USGS) is being developed to use their existing monitoring wells at various field sites through a companion project.

Objective 3 - Pathogen Regrowth

Research projects on pathogen regrowth have been conducted primarily for drinking water distribution systems (Le Chavallier et al, 1996). However, the potential for pathogen regrowth in conveyance systems used to transport sewage effluent from wastewater treatment plants to agricultural fields has not been addressed, possibly because this is a growing practice and it has not been given much thought. Thus, our objective will be to conduct field and laboratory experiments to study pathogen regrowth in wastewater distribution systems and to evaluate the factors that lead to deterioration of water quality during its transport. In addition, recommendations for the control of wastewater quality in the distribution systems will be made in order to avoid possible direct contamination of crops. Initially, we will examine only one field site but we are hopeful that this project will generate interest among the research community and regulatory agencies to expand this project in the future to evaluate other sites. Several factors will be considered in the selection of our field site, including the length of the conveyance system (>5 miles), types of crops produced (preferably fresh vegetables), and accessibility of monitoring data and sampling sites. Field data will be collected and recorded at the time of each sampling (once a week) and will include the plant's effluent production, water temperature, turbidity, pH, and disinfectant residual. Water samples (in triplicate) will also be collected from three different locations, at the plant effluent, at midpoint in the distribution system, and at the end of the distribution system. The water samples will be transported on ice to the laboratory where they will be subjected to molecular characterization of bacterial pathogens following DNA extraction and PCR procedures described in objective 1. In addition, total coliform and *E. coli* enumerations will be performed using the membrane filter method with m-Endo media following standard procedures (AWWA, 1999). Data from this study will be used to evaluate whether the number of bacteria (pathogens) in the effluent increases as it is transported from the treatment plant to the irrigated fields and to examine if there is a relationship between pathogen regrowth and any chemical, physical or biological parameters.

The purpose of the laboratory studies will be to investigate the chemical, physical and operational factors that influence the regrowth of pathogens in a distribution system through use of a bench scale model (annular reactor, BioSurface Technologies Corp.). We have chosen to use of an annular reactor as a model because it is a simple and economic simulated distribution system that has become the system of choice for monitoring biological fouling, regrowth, and biocorrosion in drinking water systems at bench scale (Camper et al., 1998; Characklis et al, 1998). In addition, its operational controls will allow us to model parameters observed in our real-time distribution system while carrying out experiments under controlled conditions that are difficult to control in the field. The annular reactor contains an inner cylinder whose rotational speed can be adjusted to provide liquid/surface shear and transport conditions similar to that of real-time water distribution systems. It also permits the control of temperature and residence time of the water and is suitable for work with pathogenic microorganisms. In this study, we will monitor water quality and bacterial regrowth by sampling the annular reactor's influent and effluent using sterile tubes. Sampling will take place weekly for approximately 8 weeks to allow for biofilm formation. The samples collected will undergo the same type of analysis as for the field samples. In addition, the annular reactor contains

detachable coupons (slides), which will permit the monitoring of coliforms and selected pathogens that may be present in the biofilms throughout the experiment. Two slides will be removed from the reactor and replaced with sterile slides to determine reproducibility of results. A series of experiments will be carried out to test the effects of temperature, nutrient levels (carbon and phosphorus availability), and/or disinfection residual on water quality. Information from this study will be used to make recommendations for sewage treatment and conveyance strategies that use parameters observed in the field so that they can be applicable to the real-time distribution system under study. Overall, this research will help ensure the absence of pathogens in irrigation water and hence, safety of the food produced.

Contingencies

The research relies on cooperation with local municipalities to obtain wastewater. Arrangements will be made with wastewater irrigation projects to permit sampling water from conveyance systems and provide treatment plant monitoring data.

Collaborations

Necessary (within ARS): collaboration with research hydraulic engineer, Herman Bouwer, at the U.S. Water Conservation Laboratory is required for site characterization and selection of field sites.

Necessary (external to ARS): none

Physical and Human Resources:

The wastewater irrigation group addressing the microbial aspects of the study consists of a microbiologist (100%) and one technician. Physical resources include 300 sq feet of lab space for the microbiologist and a dedicated greenhouse for the soil columns. The microbiology laboratory is equipped with a 5700 GeneAmp (PE Appliedbiosystems) for real-time PCR and an imaging system (Biorad) for chemiluminescent detection of gene probe hybridizations. There is also general laboratory support including a water quality chemistry lab, a soils lab, and a machine shop. Support for the column studies is also provided by a research hydraulic engineer in a related project and additional labor through a cooperative agreement with Arizona State University. Field facilities include municipal sewage treatment plants and sewage irrigated fields in Arizona and California in addition to shallow wells for sampling the upper groundwater in sewage irrigated areas west of Phoenix, Arizona.

MILESTONES AND OUTCOMES

By the end of FY2002, the initial screening of pathogens in sewage and column effluents will be completed and should determine the presence of specific pathogens of highest concern to groundwater contamination. By the end of FY2003, we expect results regarding the fate and transport of pathogens from field studies as well as the completion of pathogen regrowth assessment in distribution systems. Studies on the effects of irrigation and groundwater recharge with sewage effluent will continue until dynamic equilibrium or end conditions are reached. If adverse effects are observed, procedures for mitigating these effects will be developed and tested on the columns by FY2004 (Table 5).

Table 5. Milestones and outcomes

Research Study-Component	**Months of Study**			
	11	22	33	44
Pathogen Transport/ Column Studies	Operation and management for irrigation and groundwater recharge procedures, development of sampling and DNA extraction protocols completed	Operation continued, establish PCR procedures for selected pathogens, initial screening of pathogens going into and out of the columns completed	Operation continued, evaluation of fate and transport of pathogens completed	Final reports and manuscript prepared, develop recommendations and future studies
Pathogen Transport/ Field Studies	Site characterization and sample collection completed	Optimization of DNA extraction and analysis protocols completed	Detail sampling to valuate fate of selected pathogen(s), analysis by PCR completed	Interpretation of results, final reports and manuscript prepared, develop recommendations for future studies
Pathogen Regrowth/ Laboratory and Field Studies	Field site characterization, operation and management of annular reactor completed	Operation and sampling of annular reactor continued, sampling at different points in the water distribution completed	Molecular analysis of samples completed	Interpretation of results, final reports and manuscript prepared, develop recommendations for the control of pathogen regrowth

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WASTEWATER IRRIGATION AND GROUNDWATER RECHARGE

Herman Bouwer, Chief Engineer

PROJECT SUMMARY

Using wastewater for groundwater recharge is an attractive way for seasonal storage and additional water quality improvement through soil-aquifer treatment. The efficacy of soil-aquifer treatment for removal of organic carbon including pharmaceutically active compounds will be studied with soil columns in a greenhouse. Soil columns will also be used to study the fate of organic compounds in soil where crops are irrigated with sewage effluent. Additionally, samples of the upper groundwater below fields and urban areas (parks, golf courses, landscaping) with a long history of sewage irrigation will be taken and tested for organic agricultural compounds and pathogens.

Long-term storage of water via artificial recharge of groundwater (water banking) in times of water surplus provides a valuable source of water for use in times of water shortage. We plan to expand the potential of this technology, which is now pretty well restricted to permeable soils, to finer-textured "challenging" soils that need to be managed to minimize reductions in infiltration rates due to clogging.

OBJECTIVES

1. termine the fate of organic compounds, such as pharmaceuticals and pharmaceutically active chemicals and disinfection byproducts, in vegetated soil columns (grass and alfalfa) in a greenhouse irrigated at various efficiencies with chlorinated secondary sewage effluent. The columns will also be used to determine fate of pathogens in sewage irrigated soil under a companion project under National Program 208, Food Safety (Protecting Groundwater Quality Below Waste-Water Irrigated Fields).

2. Analyze samples of the upper groundwater below agricultural fields and urban irrigated areas (golf courses, parks, landscaping) with a long history of sewage irrigation for pharmaceuticals, disinfection byproducts and other chemicals to evaluate effects of sewage irrigation on groundwater quality. The samples will also be analyzed for pathogens under a companion project.

3. Carry out field and laboratory research to develop optimum management procedures for basins that infiltrate secondary or tertiary sewage effluent for recharge of groundwater and water quality improvement through soil-aquifer treatment. Focus will be on relatively fine-textured soils where clogging, crusting, and fine-particle movement can seriously reduce infiltration rates, and hence, recharge capacities.

NEED FOR RESEARCH

Description of the Problem to be Solved

Increasing populations and finite water resources necessitate more water reuse (Asano, 1998; Bouwer, 1993 and 1999). Also, increasingly stringent treatment requirements for discharge of sewage effluent into surface water make water reuse more attractive. The present focus in the U.S. is on sustainability of irrigation with sewage effluent and of soil-aquifer treatment, particularly the

long-term fate of synthetic organic compounds (including pharmaceutically active chemicals and disinfection byproducts) in the underground environment (Lim et al., 2000; Bouwer, 2000; Drewes and Shore, 2001). The fate of pathogens and nitrogen also needs to be better understood. In Third World countries, simple, low-tech methods must be used to treat sewage for reuse. These methods include lagooning, groundwater recharge, and intermittent sand filtration (Bouwer, 1993). While most standards or guidelines for irrigation with sewage effluent focus on indicator organisms and pathogens, other water quality aspects must also be considered (Bouwer and Idelovitch, 1987).

Long-term effects of irrigation with sewage effluent on soil and underlying groundwater must be better understood so that future problems of soil and groundwater contamination can be avoided. Potential problems include accumulation of phosphate, metals, and strongly adsorbed organic compounds to the soil matrix, and of salts, nitrate, toxic refractory organic compounds, and pathogenic microorganisms in groundwater. Water reuse for irrigation is a good practice, however, care should be taken to prevent deterioration of groundwater quality (Bouwer et al., 1999; Bouwer, 2000). Typical concentrations of some potentially endocrine disrupting chemicals in sewage effluent are shown in Table 1, taken from Lim et al., (2000). Other pharmaceuticals such as lipid regulators, antiepileptics, analgesic/anti-inflammatory drugs, and antibiotics can also be present. The microbiological safety of water reuse is also an important issue, particularly when wastewater is used for the irrigation of fruits and vegetables that are eaten raw or brought raw into the kitchen, as discussed in a companion project under National Program 108. It is of utmost importance to understand the risks associated with wastewater used for irrigation and the factors affecting the deterioration of wastewater effluent after it leaves the treatment plant. There is growing concern about the potential for microbial regrowth in the conveyance /distribution systems where the effluent is transported over long distances to the irrigated areas (mostly with pipelines). The aim of this research is to develop technology for optimum water reuse, to evaluate the role that groundwater recharge and soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent (Bouwer, 1985) and to determine the safety of tertiary effluent used for irrigation of foods, particularly where effluent is transported for relatively long distances in pipes or open channels where regrowth of pathogens and other processes can occur.

Relevance to ARS National Program Action Plan

This research directly addresses national and global problems dealing with safety of food produced in fields that have been irrigated with sewage effluent or with effluent contaminated water. It also addresses water conservation and integrated water management through water reuse. These issues occur or emerge in many parts of the U.S. and the rest of the world wherever there is not enough water to meet all demands for municipal, industrial, and agricultural (irrigation) purposes. All objectives fall under National Program 201, Water Quality and Management. Objectives 1 and 2 fall under Problem Area 2.5 (Waste Water Reuse), Goal 2.5.3 (Waste Water Standards). They address water conservation and integrated water management through water reuse. Objective 3 addresses Problem Area 2.3 (Water Conservation Management), Goal 2.3.1 (Water Conservation Technologies).

Table 1. Typical concentrations of some EDCs in treated sewage effluent (Lim et al., 2000).

Compound	Secondary Treatment	Tertiary treatment
Estrogen (ng/L)	38	3
Testosterone (ng/L)	50	2
Estrone (ng/L)	1.4 - 76	1.8 - 3.6
17β-estradiol (ng/L)	<5 - 10	2.7 - 6.3
Estriol (ng/L)	<10 - 37	
Ethyinylestradiol (ng/L)	<0.2	<0.2
Nonyl-phenol (μg/L)	<0.02 - 330	
2,4-dichlorophenol (μg/L)	0.061 - 0.16	
Alkylphenols (total)(μg/L)	27 - 98	
Bisphenol A (μg/L)	0.02 - 0.05	
Arsenic (μg/L)	1.3 - 23	
Cadmium (μg/L)	<0.02 - 150	
Lead (μg/L)	0.1 - 44	

Sources: Shore et al. 1993a, Desbrow et al. 1998, Lee & Peart 1998, Blackburn & Waldock 1995, Rudel et al. 1998, Johns & McConchie 1995, Feigin et al. 1991, Bahri 1998.

Potential Benefits

Benefits from attaining the objectives include safe reuse of sewage effluents for irrigation from the standpoint of food safety and groundwater quality protection. Control measures and actions or activities that can be used to prevent, reduce, or eliminate the microbial and chemical food safety hazard will be developed. Water reuse will be more common and the practices will be safer for public health. Such reuse will help in production of adequate food and fiber for growing populations.

Anticipated Products

1. Improved techniques of sewage treatment and system management for safe and sustainable water reuse with minimum adverse effects and in environmentally acceptable ways.
2. New guidelines for irrigation with wastewater to protect groundwater and surface water quality.

3. New procedures for managing groundwater recharge basins to improve their effectiveness, especially where soils are relatively fine-textured.

Customers

Customers of the research include the public, farmers and farm workers, water planners and managers, government regulators, consulting engineers, water districts and municipalities, wastewater treatment plant operators and managers, and the turf, landscape, and golf-course industries.

SCIENTIFIC BACKGROUND

In groundwater recharge, the quality improvements obtained as the effluent water moves downward through the vadose zone to underlying aquifers, and then through the aquifer to recovery wells for irrigation and/or potable use of the water are very important, as are the aesthetic aspects and public acceptance of water reuse. The lead scientist has been at the U.S. Water Conservation Laboratory for more than 41 years where a greater part of his research has been devoted to artificial recharge of groundwater, especially with sewage effluent. Field studies (Flushing Meadows and 23rd Avenue projects), supported by EPA grants, were conducted in the period 1967-1985, as well as numerous laboratory studies on soil columns, focusing on nitrogen transformations and virus transport. At that time, the effluent recharge team consisted of two engineers, a soil chemist, a microbiologist, and for a short period a soil physicist. This work has been published in numerous articles in peer-reviewed journals and book chapters (Bouwer et al., 1980; Bouwer et al., 1984; Bouwer and Rice; 1984) and has put the U.S. Water Conservation at the forefront of institutions in artificial recharge of groundwater and water reuse. However, new concerns have risen over the years, including sustainability issues, food safety issues involving the presence of pathogens in effluent directly used for irrigation, artificial recharge and soil aquifer treatment, trace organic compounds, and groundwater quality issues (Lim et al., 2000; Drewes and Shore, 2001; Bouwer, 2000).

Concern is growing with regard to the refractory natural and synthetic organic materials present in the sewage effluent, both for irrigation and potable use of the reclaimed water. Potable use normally involves release and dilution in natural streams and rivers or a groundwater recharge cycle after conventional primary and secondary sewage treatment. This is done for aesthetic and public acceptance aspects (indirect potable use without toilet-to-tap connection) and for additional quality improvements of the water through soil-aquifer treatment (removal or reduction of suspended solids, nitrogen, phosphorus, synthetic and natural organic carbon compounds, metals, and pathogenic microorganisms). However, not all organic compounds are biodegradable or adsorbed, leaving a residual or refractory total organic carbon concentration (TOC) of 2 to 5 mg/L (Bouwer, 1985). California guidelines for potable use of the water without additional treatments require that this concentration be reduced to less than 1 mg/L. This concentration can be achieved by treating the effluent with activated carbon or membrane filtration before infiltration for groundwater recharge, or by blending with natural groundwater in the aquifer so that the wells yield a water with not more than 1 mg/L of effluent TOC. Several studies have been conducted to identify the composition of the residual TOC (Bouwer et al., 1984; Drewes and Fox, 1999 and 2000; Schoenheinz et al., 2000). Typically, these show a wide spectrum of aliphatic and aromatic, halogenated and non-halogenated

compounds, almost all at about the parts per billion (ppb) level. In one study the pharmaceutical clofibric acid was also found (Bouwer et al., 1982). However, perhaps less than 10% of the TOC has been characterized, and there is more concern about what is not known about the residual TOC than what is known about it, even though two major health effects studies in California have not shown adverse health effects in populations where well water with less than 1 mg/L sewage TOC was used for municipal water supply (Nellor et al., 1984; Sloss et al., 1996).

When effluent is used for irrigation, all the chemicals in the effluent, not taken up by the plants and not biodegraded adsorbed or otherwise attenuated or immobilized in the root zone, are leached out of the root zone with the deep percolation water that is necessary to keep a salt balance in the root zone (Bouwer, 2000). This deep percolation water can be produced by irrigation applications in excess of evapotranspiration, or by natural rainfall. In dry climates, the volume of deep percolation water will be considerably less than the irrigation water applied, so that the concentration of salts and other chemicals not attenuated in the root zone will be higher than in the irrigation water. In dry climates, an irrigation efficiency of 80% would produce a deep percolation water with salts and other unattenuated chemicals concentrations that are five times those in the irrigation water. For irrigation with sewage effluent the sewage chemicals of concern are salts and nitrates, natural and synthetic organic compounds (including pharmaceutically active compounds), disinfection by-products (DBPs) including the potent carcinogen nitrosodimethyl amine (NDMA), and humic and fulvic acids that can act as DBP precursors when affected groundwater is pumped up again and chlorinated for potable use. Thus, it is important to study more about chemicals in deep percolation water below sewage irrigated fields so that the potential long-term effects on groundwater can be better predicted and the sustainability of water reuse for irrigation can be better assessed. Membrane filtration of the effluent before irrigation, or of the underlying groundwater where needed for potable use, may eventually become necessary. Irrigation efficiency may play a role in this because while higher concentrations of organic compounds in the deep percolation water may be undesirable, they can also be an advantage if the concentrations become high enough to trigger enzyme expression required for biodegradation by indigenous microorganisms. However, when sewage effluent is used for groundwater recharge, evaporation normally is negligible compared to infiltration, so that concentrations of refractory organic compounds are not increased which may keep them below threshold concentrations for enzyme expression and biodegradation by bacteria.

Where soils are fine-textured and limit the rate of recharge to groundwater, larger infiltration areas that can be combined with wetlands or stream channels may be used to recharge the groundwater. This approach, however results in additional freshwater losses to evaporation and transpiration. Maintaining maximum recharge rates may help to improve the effectiveness of these systems and could extend the benefits of artificial recharge of groundwater and long-term underground storage (water banking) to desert and agricultural areas where sands and other permeable soils are not available (Bouwer 1998). In general, groundwater recharge and soil-aquifer treatment (SAT) systems are fairly robust. From a practical standpoint, we want to avoid very tight soils, very coarse soils, very shallow or very deep groundwater tables, low transmissivity aquifers, geochemical incompatability between infiltrated water and aquifer, and situations with vadose zone or groundwater pollution problems, or where the recharge will cause "unreasonable" harm to other land owners or users, such as land subsidence or damaging high groundwater levels.

A CRIS search of active projects on groundwater recharge identified 22 projects, of which 2 are from this research unit. A majority of the rest deal with natural recharge or return flows from irrigation, and not with artificial recharge systems. Several project dealing with conjunctive use, primarily in the Great Plains, deal with issues that are closely related to this project. Of particular interest is recharge along the South Platte River in Colorado. Conjunctive use is being studied there by Colorado State University. Their results would likely have an impact on our assessment of the value of groundwater recharge. There are 9 CRIS projects on irrigation with wastewater, 2 of which are at the U.S. Water Conservation Laboratory. The project at Mississippi State University with swine effluent is of interest to the microbiologist aspects, including survival of pathogens in the soil. Foliar damage to tree species is studied in Reno, Nevada (2 projects). Effects of irrigation with paper mill effluents on soil are studied in Flagstaff, Arizona. Enhanced pesticide transport in soils irrigated with sewage effluent is studied at Purdue University. Swine waste treatment is studied at Honolulu, while the group at Fresno develops management practices to minimize adverse effects of irrigation with normal water on soils and groundwater. These are all considered complementary to the research proposed herein.

APPROACH AND RESEARCH PROCEDURES

Objective 1 - Fate of Organic Compounds

Experimental Design

Technologies based on previous research at the U.S. Water Conservation Laboratory (USWCL) and other more recent research will be applied to new and existing groundwater recharge and water reuse principles and projects here and abroad. Main purposes of the reuse projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes. Ten soil columns in 2.4m x 0.3m stainless steel pipes have been set up in a greenhouse at the USWCL to study movement of pathogens and chemicals (including trace organics) in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and recharge and irrigation with Colorado River water. The columns were filled with a sandy loam from the McMicken Flood Control reservoir northwest of the City of Surprise. This is a desert soil in the Mohall-Laveen Association that has had no agricultural use. The hydraulic conductivity of the soil was determined with a laboratory permeameter test as 280 mm/day, using a disturbed sample. To avoid particle segregation, the soil was placed in the columns in air-dry condition, lowering it in a container and tipping the container when it rested on the bottom of the pipe and then on the top of the soil as the column was filled. The new soil was then compacted with a rod.

The sewage effluent to be used in the column studies should be representative of typical treatment for irrigation. As a minimum, the effluent should have had primary and secondary treatment followed by chlorination. Coagulation and granular medium filtration before chlorination should makes this so-called tertiary effluent suitable for unrestricted irrigation. This includes irrigation of lettuce and other crops consumed raw or brought raw into the kitchen, and of parks, playgrounds, golf courses and residential yards. Also the effluent should primarily be of residential origin with not much industrial input. Proposed irrigation and recharge studies of the 10 columns are shown

in Table 2 (Columns 9 and 10 are discussed under Objective 3). Initially, there will be no replications since variability issues theoretically do not exist. Because of space and other physical limitations, only ten columns could be set up. Thus, the schedule in Table 2 was developed so as to include as many different treatments as possible, including different crop and soil conditions (legume, non-legume, and bare soil), different modes of water application (irrigation and recharge, different irrigation efficiencies, and different sources of water (effluent and Colorado River water). The irrigation efficiencies in Table 2 will be determined as ET divided by amount of water applied and expressed as a percentage. ET will be calculated from the weight loss of the column as measured with load cells on which the columns are resting. Estimates of irrigation efficiency will also be obtained from EC values of irrigation water and leachate. Depending on the results, however, some replicated treatments may be used in the future to firm up some of the conclusions.

Table 2. Schedule of irrigation and recharge studies for soil columns in greenhouse.

Irrigation			
COLUMN	**COVER**	**IRRIGATION EFFICIENCY**	**WATER SOURCE**
1	grass	50%	effluent
2	grass	70%	effluent
3	grass	90%	effluent
4	alfalfa	50%	effluent
5	alfalfa	70%	effluent
6	alfalfa	90%	effluent
7	bare soil	70%	effluent
8	grass	70%	Colorado River
Groundwater Recharge			
9	bare soil	maximum loading	effluent
10	bare soil	maximum loading	Colorado River

Since U.S. Water Conservation Laboratory and ARS do not have analytical capability for the detection of trace amounts at the part per trillion (ppt) levels of synthetic organics such as pharmaceuticals and pharmaceutically active chemicals contributed to the effluent by human and industrial waste, preliminary tests have been conducted by the Civil and Environmental Engineering Department at the University of California at Berkeley, California, where Dr. David L. Sedlak has an active research program on pharmaceuticals in sewage effluent. The first sample was taken from the Goodyear treatment plant because the effluent there was also used for landscape irrigation and artificial recharge of groundwater. The treatment process consisted of primary and secondary

treatment, sand filtration, and UV disinfection. The sample was taken in mid-August in the late morning when the sewage flow was still relatively small. The results showed very low concentrations of pharmaceuticals (Table 3), about an order of magnitude less than what is found in San Francisco Bay area sewage effluents, and close to detection limits, which are normally in the 5-10 ng/L range.

Table 3. Concentrations of selected pharmaceuticals in Goodyear effluent.

Pharmaceuticals	Concentrations
ibuprofen	17 ng/L
naproxen	22 ng/L
gemfibrozil	24 ng/L
ketoprofen	12 ng/L
diclofenac	30 ng/L
indomethacine	<3 ng/L
metoprolol	20 ng/L
propranolol	7 ng/L

A better effluent for the column studies may be from the Tolleson sewage treatment plant, which also receives mostly residential sewage and gives only the more typical conventional primary and secondary treatment and chlorination. A sample was sent to the University of California Berkeley for analysis of pharmaceuticals, which showed that the concentrations were more in line with typical values (Table 4). Hence, Tolleson effluent will be used in the column studies. In a companion project, the secondary effluent and the drainage water from the columns will also be analyzed for pathogens using PCR technology since viruses are not always retained by the soil matrix and have a higher potential to migrate to underground aquifers. Overall, these studies will help determine the factors affecting microbial and chemical contamination of groundwater in order to protect our future water resources.

Table 4. Concentrations of selected pharmaceuticals in Tolleson effluent.

Pharmaceuticals	Concentrations
ibuprofen	247 ng/L
naproxen	699 ng/L
indomethacine	55 ng/L
metoprolol	133 ng/L

Contingencies

Arrangements were made with the Central Arizona Water Conservation District to obtain Colorado River water from the Central Arizona Project (CAP) Aqueduct at a point where the canal has 100% Colorado River water. The CAP water has been applied in a recharge mode to one column, starting February 10, 2000. This research also relies on cooperation with local municipalities to obtain wastewater and with various collaborators to conduct some chemical analyses. Studies on groundwater recharge rely on field sites of water purveyors. Alternative collaborators may be easily be found.

Collaborations

- Necessary (within ARS); collaboration with microbiologist, Norma Duran, at the U.S. Water Conservation Laboratory is required for the study of pathogens, as described in her Project Plan under National Program 108.

- Necessary (external to ARS); Collaboration with the U.S. Geological Survey is being developed to analyze the water samples for the column and field studies for pharmaceuticals. The USGS has several laboratories and analytical equipment (GC with MS-MS in tandem) for detection levels of 1 to 100 part per trillion (ppt). The USGS has applied for a District Special Initiative Fund to help pay for the analyses, which will also be partly funded by ARS. The analyses will cover a wide spectrum of chemicals, including pharmaceuticals, antibiotics, hormones and hormonally active compounds, disinfection byproducts, and synthetic organic compounds (Table 5). General collaboration will be established with the National Center for Sustainable Water Supplies in the Civil and Environmental Engineering Department of Arizona State University, Tempe, Arizona.

Table 5. Target compounds for USGS National Reconnaissance of Emerging Contaminant US streams

Veterinary and Human Antibiotics	
Tetracyclines	**Sulfonamides**
Chlortetracycline	Sulfachlorpyridazine
Doxyclycline	Sulfamerazine
Oxytetracycline	Sulfamethazine
Tetracycline	Sulfathiazole
Flouroquinolones	Sulfadimethoxine
Ciprofloxacin	Sulfamethiazole
Enrofloxacin	Sulfamethoxazole
Norfloxacin	**Others**
Sarafloxacin	Lincomycin
Macrolides	Trimethoprim
Erthromycin	Carbadox
Erthromycin-H20 (metabolite)	Virginiamycin
Tylosin	Amoxicillin
Roxithromycin	Spectinomycin
	Ivermectin
	Roxarsone

Human Drugs	
Prescription	**Non-Prescription**
Metformin (antidiabetic agent)	Acetaminophen (analgesic)
Cimetidine (antacid)	Ibuprofen (anti-inflammatory, analgesic)
Ranitidine (antacid)	Codeine (analgesic)
Enalaprilat (antihypertensive)	Caffeine (stimulant)
Diltiazem (antihypertensive)	Paraxanthine (caffeine metabolite)
Fluoxetine (antidepressant)	Cotinine (nicotine matabolite)
Paroxetine (antidipressant, antianxiety)	
Furosemide (diuretic)	
Warfarin (anticoagulant)	
Salbutamol (antiasthmatic)	
Gemfibrozil (antihyperlipidemic)	
Dehydronifedipine (antianginal metabolite)	

Industrial and Household Wastewater Products	
Insecticides	**Polycyclic aromatic hydrocarbons (fossil fuel and fuel combustion indicators)**
Diazinon	Napthalene
Carbaryl	Phenanthrene
Chlorpvrifos	Anthracene
cis-Chlordane	Fluoranthene
N,N-diethyltoluamide (DEET)	Pyrene
Lindane	Benzo(*a*)pyrene
Methyl parathion	**Antioxidants**
Dieldrin	2,6-di-tert-Butylphenol
Plasticizers	5-Methyl-1H-benzotriazole
bis(2-Ethylhexyl)adipate	Butylatedhydroxyanisole (BHA)
Ethanol-2-butoxy-phosphate	Butylatedhydroxytoluene (BHT)
bis(2-Ethylhexy)phthalate	2,6-di-tert-Butyl-p-benzoquinone
Diethylphthalate	**Others**
Triphenyl phosphate	Tetrachloroethylene (solvent)
Detergent metabolites	Phenol (disinfectant)
p-Nonylphenol	1,4-Dichlorobenzene (fumigant)
Nonylphenol monoethoxylate (NPEO1)	Acetophenone (fragrance)
Nonylphenol diethoxylate (NPEO2)	*p*-Cresol (wood preservative)
Octylphenol monoethoxylate (OPEO1)	Phthalic anhydride (used in plastics)
Octylphenol diethoxylate (OPEO2)	Bisphenol A (used in polymers)
Fire retardants	Triclosan (antimicrobial disinfectant)
Tri(2-chloroethyl)phosphate	
Tri(dichlorisopropyl)phosphate	

Sex and Steroidal Hormones	
Biogenics	**Pharmaceuticals**
17*b*-Estradiol	17*a*-Ethynylestradiol (ovulation inhibitor)
17*a*-Estradiol	Mestranol (ovulation inhibitor)
Estrone	19-Norethisterone (ovulation inhibitor)
Estriol	Equilenin (hormone replacement therapy)
Testosterone	Equilin (hormone replacement therapy)
Progesterone	**Sterols**
cis-Androsterone	Cholesterol (fecal indicator)
	3*b*-Coprostanol (carnivor fecal indicator)
	Stigmastanol (plant sterol)

Objective 2 - Upper Groundwater Samples

Experimental Design

This is a reconnaissance-type project. Sites for sampling upper groundwater below agricultural fields and golf courses and other urban green areas with a long history of sewage effluent irrigation will be selected on the basis of depth to groundwater (preferably shallow), availability of wells that pump primarily upper groundwater, and cooperation with farmers, irrigation districts, and municipalities. The USGS already has several wells which were sampled for pesticides and industrial contaminants, and which can be used for our studies as well. In addition to natural and synthetic organic compounds (pharmaceuticals, pesticides, etc.), samples will also be analyzed for EC, DOC, and nitrate and possibly other forms of nitrogen. As much information as possible will be obtained about cropping patterns, fertilizer applications, irrigation practices, EC of irrigation water and groundwater, irrigation efficiency, use of herbicides and pesticides, and other agronomic practices.

Contingencies

Arrangements will be made with irrigation districts, municipalities, and landowners to permit sampling water from existing wells. There is enough interest in the effect of sewage irrigation on groundwater that adequate cooperation should not be a problem.

Collaboration

- Necessary (within ARS); collaboration with microbiologist, Norma Duran, at the U.S. Water Conservation Laboratory is required for the detection of pathogens, as described in her Project Plan under National Program 208.

- Necessary (external to ARS); collaboration with the U.S. Geological Survey (USGS) is being developed for chemical analysis of the groundwater samples. The USGS is interested in this because it would be an extension of their NAWQA (National Water Quality Assessment) Program. Focus will be on synthetic and natural organic compounds such as pharmaceuticals, hormones, and hormonally active compounds. General collaboration will also be established with the National Center for Sustainable Water Supplies in the Civil and Environmental Engineers, Department of Arizona State University, Tempe, Arizona.

Objective 3 - Optimum Management Procedures

Experimental Design

Management of groundwater recharge basins: Groundwater recharge of surplus waters (excess river flows, municipal wastewater, etc.) provides an alternative to surface reservoirs for storing water and also provide a mechanism for treating water. A number of unanswered questions are faced with projects that artificially recharge groundwater, including; How much of the recharged groundwater can be recovered? What reduction in quality of the reclaimed water results from the recharge project? Does the recharge water degrade existing groundwater supplies?

Laboratory and field studies will be initiated to develop best management practices for groundwater recharge basins in relatively fine-textured soil where reductions in infiltration rates must be minimized. Emphasis will be on crusting and fine-particle movement (wash out-wash in) in the upper soil profile. Laboratory studies will use 10-cm diameter columns to study basic aspects of wash out-wash in processes such as fine particle movement and accumulation for different soil types and different simulated soil management practices (drying, disking, rolling, etc.). Studies will also be done on small field plots ranging in size from 1 m^2 to about 10 m^2, and on small experimental basins (about 10 x 100 m) which are to be installed as part of a larger recharge system for the effluent of the City of Surprise South Wastewater Treatment plant. The City of Surprise received a research grant from the Arizona Department of Water Resources for this project, with our research unit as a cooperator. Various tillage and management practices will be tested to see how fine particle movement occurs, how it can be minimized, and how infiltration rates can be maximized. The standard practice is to have roughly 30 cm water on the basins for 5 days (wet) followed by 3 to 4 days dry and disking the basins every 8 to 12 months. Modified practices include; extending or reducing the wet period, extending the dry period, varying the water depth, disking more or less often, ripping, scraping, and rolling. The number of basins and treatments will be decided as the project unfolds. The basins will be narrow and long to allow disking and other management practices with regular farm equipment. About 10 such basins will be constructed. The basins will be calibrated as to their infiltration potential, so that results of various treatments can be expressed relative to the original infiltration rates. Infiltration rates will be determined from inflow rates or as fall of the water level at zero inflows, corrected for evaporation. Hydraulic gradients in the soil to indicate surface or deeper clogging of the soil will be measured with tensiometers at different depths. The work will be cooperative with City of Surprise personnel. Construction is expected to begin in August 2001. This is essentially a two-year project (which has been delayed a year and a half because of water rights issues). Depending on the results of this study, we will pursue further projects of this kind.

Water quality improvement through infiltration of sewage effluent for groundwater recharge and soil-aquifer treatment will be studied on 2 large soil columns in the greenhouse (columns 9 and 10 in Table 2). The Colorado River water column will primarily be used to study underground fate of organic carbon analyzed as total organic carbon in the water and its potential for disinfection byproduct formation (tribalomethanes, haloacetic acids, NDMA) when the water after soil-aquifer

treatment is chlorinated or otherwise disinfected for potable use. The sewage-effluent column will be used to study the fate of pharmaceuticals in the vadose zone where sewage effluent is used for artificial recharge of groundwater.

Contingencies

Studies on groundwater recharge rely on field sites of water purveyors. Alternative collaborators may easily be found.

Collaborations

- Necessary (within ARS); No necessary collaborators.
- Necessary (external to ARS); City of Surprise AZ. (Letter of intent attached).

Physical and Human Resources

The wastewater irrigation group consists of a research engineer (LS) (100%) and a part-time technician support. Support for the column studies is also provided by a microbiologist and physical science technician on a related research project specifically studying pathogens. There is also general laboratory support including a water quality chemistry lab, a soils lab, and a machine shop. Field facilities include sewage treatment plants and sewage irrigated fields in Arizona and California, and shallow wells for sampling the upper groundwater in a sewage irrigated area west of Phoenix. Additional labor for the column studies is provided through a cooperative agreement with Arizona State University.

MILESTONES AND EXPECTED OUTCOMES

Milestone Time Line: Publication and presentation of results as significant outcomes arise. Demonstration and training programs will be held with potential users as required (Table 6).

Information should be available on the underground fate of sewage chemicals like synthetic and natural organic compounds below sewage irrigated fields and their potential effect on groundwater below sewage irrigated fields or infiltration basins used for artificial recharge of groundwater with sewage effluent. Depending on the results, these outcomes should have a significant effect on water reuse practices around the world, either giving them the green light or a warning about potential adverse effects on human health and underlying groundwater. If the latter is true, best management practices will be developed and tested. The pathogen aspects will be the responsibility of the microbiologist on a related project. The organic chemical aspects of recharge and soil-aquifer treatment systems, as well as principles and practices of water reuse and groundwater recharge in general will be the responsibility of the engineer and chemist.

Since the research addresses practical and real-world problems, it should not be difficult to translate the results into useful concepts. Additional investigations are needed and will be added to the project as funds become available.

National Collaboration

Depending on the results of the column studies and local field studies, the project will be expanded to other field sites in the U.S. and other countries. Preliminary contracts have already been established. This project is also relevant to projects within ARS that focus on manure handling and utilization and could lead to collaboration with other ARS laboratories such as the Natural Resources Institute, Beltsville Area.

ARS is in the process of establishing an initiative on the use of wastewater for irrigation, which is supported by the Irrigation Association. The initiative intends to establish related research projects at Bushland, TX and Florence, SC.

Table 6.

Research Study Components	end of year 1	end of year 2	end of year 3	end of year 4	end of year 5
Greenhouse soil columns	operation, management and sampling for irrigation and groundwater recharge procedures, chemical analyses, program completed	operation, continued results of chemical analysis interpreted changes in column management as indicated, consider applying animal manure and analyze inflow and outflow for pharmaceuticals	operation continued, manuscripts prepared, spiking infiltration water with tracers and specific chemicals	final reports and manuscript prepared, plan and perform future studies	final reports and manuscript prepared, plan and perform future studies
Field reconnaissance	select sites of wastewater irrigated fields and urban areas and sample water and groundwater for wastewater chemicals	include more sites in other parts of the U.S.	expand sampling program to other countries	prepare final reports for presentation and publication of papers, plan and perform future studies	prepare final reports for presentation and publication of papers, plan and perform future studies
Clogging research	set up laboratory and field studies for soil clogging and mitigation in recharge basins, study crusting and fine particle movement	continue laboratory and field studies for maximizing infiltration rates in fine-textured soils	continue laboratory and field studies for maximizing infiltration rates in fine-textured soils	write papers on best management practices, plan and perform future studies	write papers on best management practices, plan and perform future studies

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SURFACE IRRIGATION WATER QUALITY AND MANAGEMENT

Theodor S. Strelkoff, Research Hydraulic Engineer
Floyd J. Adamsen, Soil Scientist
Eduardo Bautista, Research Hydraulic Engineer
Douglas J. Hunsaker, Agricultural Engineer
Albert J. Clemmens, Research Hydraulic Engineer
Robert J. Strand, Electrical Engineer
Hadi Tabbara, Soil Scientist

PROJECT SUMMARY

Surface irrigation is the most widely used irrigation method in the world. In the US, over 50% of irrigated land is watered by surface means. It is the most inexpensive method, in terms of capital outlay, power requirements, and maintenance costs. Traditional surface methods are labor intensive. Poor uniformity of application, and excessive runoff and deep percolation, often carrying agricultural chemicals into the environment, are common. The complexity of the hydraulics of surface systems has, until recently, made rational design very difficult. Accordingly, many surface systems are built and operated without the benefit of any technical design. The proliferation of computers has now made numerical solutions of the hydraulic equations easily attainable, and is putting design of surface irrigation systems and their operation on a par with other engineering disciplines -- with reliance on multiple analyses (simulations) with trial values of the design variables in the search for an optimum.

The proposed research is intended ultimately to provide guidance in the design and operation of surface systems, both traditional and innovative. The investigators will collaborate with several ARS sites addressing all four of the NP201 research initiatives. Intermediate goals are (1)simulation of the transport and fate of water, sediments, and nutrients such as phosphorus and nitrogen by irrigation in furrows, border strips, and basins of various types, along with attendant field studies,(2) software for presenting overviews of simulations to aid in the search for an optimum, (3) software to assist in evaluating extant field conditions on which irrigation performance depends.

OBJECTIVES

1. Develop validated software (a) for simulating surface-irrigation hydraulics, (b) for assisting in design and management of such systems, and (c) for estimating the field parameters that bear upon system behavior.
2. Develop guidelines for design and operation of drain-back and other surface-drained level basins to improve water use in surface irrigation, while maintaining farm profitability and sustainability.
3. Develop validated surface-irrigation models incorporating the fate and transport of sediments, phosphorus, and nitrogen, including their ultimate off-site discharge.
4. Develop guidelines for water and nutrient management under surface irrigation for minimizing introduction of nitrogen into surface and ground waters while maintaining soil fertility, crop yields, and farm profitability and sustainability.

NEED FOR RESEARCH

Description of the Problem to be Solved

Surface irrigation accounts for half of the irrigated land area in the U.S. and over 90% worldwide. Many systems are built and operated without adequate technical input, with consequent low uniformity and efficiency of water application. Yet, water supplies for irrigation are limited and likely to decline due to competition from environmental and urban water demands. Improved management and conservation will be required to maintain current levels of crop production; at the same time, demand for food is expected to grow. Science-based criteria for design and management of surface

systems can often improve surface irrigation performance to levels commensurate with pressurized systems at substantial savings in capital costs and energy. Irrigated agriculture also contributes to non-point source pollution of groundwater and surface waters with nitrogen and phosphorus. Application of nitrogen fertilizer in the irrigation water is widely practiced but often leads to nonuniform, excessive application and contributes to nitrogen contamination of the groundwater. Tailwater runoff can carry sediments, nitrogen, and phosphorus to surface streams. Improved design and operation of surface irrigation systems and improved nitrogen application practices should improve agriculture's utilization of water and reduce its adverse effects on the environment.

Relevance to ARS National Program Action Plan

The research is part of NP201, Water Quality and Management. The project falls under Component 2, Irrigation and Drainage Management. Objectives 1 and 2 deal with agricultural water conservation, while 3 and 4 deal with the effects of irrigated agricultural on the environment. All fit under Problem Area 2.3 (Water Conservation Management), Goal 2.3.3 (Agricultural Water Conservation and Environmental Quality). Objective 3 concerns also Problem Area 2.6 (Erosion on Irrigated Land), Goal 2.6.2 (Irrigation/Erosion Model).

Potential Benefits

Process-based predictive tools can be effectively used to examine the consequences of various system designs and management practices on the utilization of water and nutrients by the crop and on the contamination of surface water and groundwater by irrigated agriculture. These tools can become the basis for improving practices that conserve water, minimize fertilizer costs, and protect the environment, while maintaining yields of crops under irrigation, particularly with surface methods.

Anticipated Products

1. A process-based model of surface irrigation, including water flow, sediment movement, and the movement over the field surface of chemicals, both dissolved in the water and attached to sediment particles. For studies on fate and transport of nitrogen, the model is to be linked with other models, developed at collaborating laboratories, simulating soil physical and chemical processes.
2. Design and management-aid software, integrated with the simulation model.
3. Guidelines and recommendations, grounded in contemporary scientific and engineering principles, for improving surface irrigation performance and for reducing the impact of irrigation on the environment, while maintaining or improving crop production and quality.

Customers

The NRCS (Natural Resources Conservation Service, particularly through the National Water and Climate Center and Thomas L. Spofford, Irrigation Engineer) has supported our development of surface-irrigation design and management tools and has promoted these for use at its field offices. We thus expect our main customers to be the NRCS, as well as agricultural consultants, mobile field labs,

and extension agents, with farmers as the ultimate beneficiaries (particularly in the case of software). We plan to have these groups review the software and predictive tools throughout the development process, as well as the ultimate recommended practices.

SCIENTIFIC BACKGROUND

Objective 1 - Irrigation Software

Simulation models are used to aid system design and management. The most widely disseminated, covering all of the phases of an irrigation and forming a basis for constituent transport, are the one-dimensional SIRMOD (Utah State University, 1989) and SRFR (Strelkoff et al, 1990). An uncounted number of additional, ad-hoc constructions are built for specific applications (e.g., Fernandez, 1997). One-dimensional models are those in which the pertinent variables are considered functions of a primary (longitudinal) direction, such as distance down a furrow or border strip, and time (in contrast, a typical two-dimensional problem might deal with a large basin with a point inlet, the inflow spreading out in all possible directions). SRFR accommodates spatially and temporally varying slopes, cross sections, infiltration and roughness, as well as a variety of inflow-management strategies -- cutback, surges, cablegation, and drainback. A selection of infiltration, roughness, and plant-drag formulations are available. Irrigation-stream responses to field and inflow conditions such as front-end recession and re-advance are accommodated. In 1998, a mouse/menu-driven version with graphical user interface was released (Strelkoff et al, 1998).

For given field conditions (topography, infiltration, roughness) and water availability at the site, performance (which includes efficiency, uniformity, water cost per hectare, etc.) is a function of the design variables. That functionality, which can be imagined for each performance variable as a response surface, can be explored informally, by trial and error. The engineer tries different combinations of the design variables and calculates simulated performance level for each. In a more direct, inverse, procedure (BASIN, Clemmens et al., 1995), the engineer specifies a desired performance level, and the program, interpolating within a database of previously run simulations, quickly calculates the values of the design variables which achieve that level. In another approach, the engineer specifically seeks the maximum point of the response surface. Then, in a formal optimization procedure (e.g., Wallender et al., 1990), a simulation model is called repeatedly in an automated search for the maximum. A more recent development (BORDER -- Strelkoff et al, 1996) provides performance overviews, which present the response surface itself to the viewer, as contours, again, obtained by interpolation within a massive database of simulation results. These are intended to span the practical range of field and design variables of interest, and are "hardwired" into the program. Such a static database is limited by the specifics under which the simulations were run (even with the enormous generality afforded by use of dimensionless representations).

Estimation of Field Parameters

Infiltration and hydraulic drag are essential soil-boundary conditions on the irrigation stream and constitute inputs to simulation and design/management software.

Infiltration: Surface-irrigation modelers and evaluators have mostly relied upon the wholly empirical Kostiakov power law in time, for cumulative infiltration (volume per unit infiltrating area), often modified (Lewis, 1937) by a long-time, *basic* rate, and sometimes a constant, to account for soil cracks. The Kostiakov-Clemmens branch function (Kostiakov, 1932; Clemmens, 1981) is the simple power law at small times, but crosses to a constant final rate at the time the power-law rate matches the long-term rate. It fits some soils better than the Kostiakov-Lewis formula. With these formulas, great flexibility in matching observed infiltration is provided by as many as 3 independent empirical parameters, but selecting 3 values also presents a challenge.

The SCS (now, NRCS – USDA, 1974) proposed a set of infiltration *families* for all soils to fit, each member with a specified coefficient and exponent in the Kostiakov power law. The families proved easy to use, and many engineers learned to associate the soils in their region to specific families. Not surprisingly, many soils fail to fit any of the families, and in response, Merriam and Clemmens (1985) introduced the Time Rated Intake Families for non-cracking soils. These families were based on an empirical correlation (fitted with an algebraic equation) between the time to infiltrate just 100 *mm* and the Kostiakov exponent. A single measurement, of the time required to infiltrate the 100 *mm*, provides a Kostiakov cumulative infiltration function.

In simulating furrow flow, the fundamental infiltration boundary condition required as a function of time is the volume infiltrated per unit length, A_z, rather than volume per unit infiltrating area, z. In a theoretical (Richards, or Green and Ampt) approach to furrow infiltration the obvious direct dependence of A_z upon wetted perimeter comes out as part of the solution (Enciso et al, 1991; Peck and Talsma, 1968; Talsma, 1969; Youngs, 1972; Freyberg, 1983; Philip, 1984; Schmitz, 1993a,b,). In one popular empirical approach (Elliot and Walker, 1982; Walker and Humpherys,1983), A_z is directly determined for a series of time values by dividing the corresponding measured infiltrated volumes V_z in a furrow test section by its length. For a flow depth other than in the test, the necessary modification is not clear. The SCS, on the other hand, identifying a *soil* by its family, *calculates* the effect of furrowing on infiltration by multiplying the family z by an "empirical" wetted perimeter, whose value can be as much as 2 or 3 times the actual furrow wetted perimeter (USDA, 1985; Strelkoff, 1992). In SRFR, infiltration is approximately characterized by empirical z parameters, and in a time step of simulation, the increase in z is multiplied by the extant wetted perimeter to compute the corresponding increase in A_z. The theoretical implications of this practical device are unclear.

Point measurements of infiltration seldom identify representative field values suitable for simulating an entire event. There are two basic approaches to estimating field infiltration and roughness from irrigation-stream observation. In one, inflow and outflow are measured, along with enough time-varying stream geometry to apply mass balances and determine the time rate of infiltration into the soil (Finkel and Nir, 1960; Maheshwari et al, 1988; Gilley, 1968; Roth et al, 1975; Fangmeier and Ramsey, 1978, Strelkoff et al, 1999). In the other, only selected features of stream behavior, e.g., inflow and advance and possibly a stream-flow depth, are measured and compared with simulated stream behavior, to deduce the field parameters (Shepard et al, 1993; Elliott and Walker, 1982; Clemmens, 1991; Walker and Busman, 1990; Bautista and Wallender, 1993; Clemmens and Keats, 1992; Clemmens, 1992, Scaloppi et al, 1995; Clemmens, 1981; Monserrat and Barragan, 1998; Valiantzas, 1994; Yost and Katopodes, 1998; Katopodes et al, 1990, Playan and Garcia-Navarro,

1997). The basic problem with the first method is the intensive field work required. The problem with the second is the uncertainty over whether the deduced field parameter values are at all correct. An error in estimating infiltration from measured advance can be compensated, in a particular event, by adjusting the roughness. With what certainty does an automatic optimization technique lead to a *global* minimum of errors, rather than a local depression (Katopodes, 1990; Katopodes et al, 1990)? How does actual spatial variability influence an assumed spatially uniform deduced value? The ultimate practical question is: what are the most *advantageous* measurements to obtain sufficiently accurate estimates of field properties with minimum effort.

Hydraulic Drag/Roughness: Many of the same considerations apply to estimation of surface roughness and plant drag, with the general understanding that it is not quite as important an issue as infiltration, partly because it does not vary as much as infiltration, and partly because in some cases (sloping border strips) errors in estimation partially cancel (Fangmeier and Strelkoff, 1979).

SRFR Suite: Many of the problems associated with collecting simulation, design/management, and field-parameter estimation into a single Windows-based suite with data crossing easily between components have been anticipated by the U.S. Corps of Engineers' Hydrologic Engineering Center, which is in a program of updating its software (NexGen project) to integrated, multiplatform, object-oriented status. An alternative to recoding hundreds of thousands of lines of Fortran legacy code is *wrapping* sections of such code in, e.g., Java so they can be treated as objects by the integrated shell (Davis, 2000). An amalgamation of soil-erosion models into an integrated package is found in MOSES (Meyer et al, 2001). Interactive data entry permits consideration of small watersheds, larger than the field/farm scales associated with earlier versions of its component modules. An integrated package of hydrologic and erosion models is also described in Ascough II et al, 2001.

Objective 2 - Surface-Drained Level Basins

The advantages of laser-graded level basins in improving water-distribution uniformity, application efficiency, and crop yields are documented (Dedrick, 1984; Clemmens, 2000), and software to aid in their design has been released (Clemmens et al, 1995). The relatively high costs of conversion, the large depths that must sometimes be applied to achieve high uniformity, and the danger of crop damage from undrained precipitation are all mitigated by a modification, *drainback*, which provides both inflow and outflow through a single broad, shallow ditch running down the prevailing slope, alongside a series of benched level basins, each irrigated and drained in turn. In this way, a portion of the applied water is returned to the supply channel before excessive infiltration has occurred (Dedrick, 1983; Dedrick and Clemmens, 1988). Such systems, developed at the USWCL in the 1980s, are expanding rapidly in central Arizona. The flow in a level-basin with drainback is essentially one dimensional, and its simulation has been programmed into SRFR. Some field studies have been conducted, but no general design and operational guidelines are available.

A further modification, developed in northern Louisiana where surface drainage is essential, is characterized by a square grid of shallow *spin ditches,* so called because the excavated material is spun out over the surrounding land to avoid berms on the banks, facilitating both water supply to the interiors of the grids and drainage (Clemmens, 2000). Thus, both supply and drainage occur

throughout the basin. The effectiveness of these spin ditches, required spacing, etc., have not been studied. As a result, NRCS is reluctant to endorse them, even though farmers are pleased and acreage is expanding.

The flows in grid-supplied and drained level basins are essentially two-dimensional. A two-dimensional treatment of a dambreak flood on irregular topography was presented by Xanthopoulos and Koutitas (1976). The zero-inertia formulation therein, described by a parabolic partial differential equation, precludes true wave dynamics, but allows theoretically correct inclusion of both wet and dry areas into the calculation. Their work, however, incorrectly treats the vector components of hydraulic resistance. The first two-dimensional fully hydrodynamic model explicitly considering advance on a dry bed was the characteristics-based dam-break-flood model of Katopodes and Strelkoff (1978, 1979). Dam-break models were built by Hromadka and Yen (zero-inertia, 1986), Akanbi and Katopodes (finite elements, 1988), and Bellos et al (finite-difference MacCormack scheme applied to irregular quadrilaterals transformed to rectangles, 1991). The full hydrodynamic leapfrog solution of Playan et al (1994), extended to irregular topography (1996), requires postulation of a small depth everywhere initially with the tacit assumption that the surge of irrigation water advances as a hydraulic bore over this small depth. The authors expressed some concern about the theoretical satisfaction of boundary conditions, in view of the neglect of a momentum-conservation relation there.

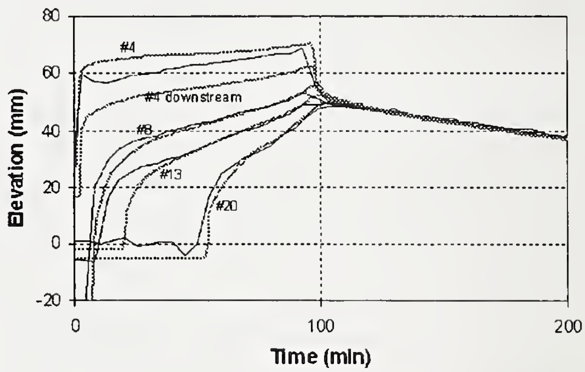

Figure 1. Simulated (broad line) and measured (fine line) water-surface elevation hydrographs at selected points in basin (Clemmens and Strelkoff, 2001)

Strelkoff et al (2001) utilized the zero-inertia approximation to avoid both the fictitious initial film of water and characteristics-based equations at the boundary. Furthermore, to permit large time steps, they developed an implicit numerical scheme with an alternating-direction solver for the resulting system of simultaneous linear algebraic equations. However, despite theoretical determinations of unconditional stability, computational experience shows that to avoid growing oscillations, especially in the neighborhood of deep depressions in the soil surface, time steps must be small, especially with fine spatial grids. Nonetheless the scheme provides useful simulations. Figure 1 shows a comparison of simulated and measured depth hydrographs at selected points in a 4 hectare basin (Clemmens et al (2001). Of note, computational points *#4* and *#4downstream* straddle the field depth sensor which supplied the measured hydrograph plotted between them.

Objectives 3 - Fate and transport of sediment, phosphorus, and nitrogen

Sediment: The Water Erosion Prediction Project (WEPP – USDA, 1995) is a process-based model primarily of rainfall-induced soil erosion. It appears not very well suited to surface-irrigation-induced erosion. The NRCS, while planning implementation of the hydrologic-erosion WEPP model in its watershed program, has found WEPP's surface irrigation component unvalidated and unacceptable

(Spofford, NRCS, 1995, 1998). Bjorneberg et al., 1999, and Strelkoff and Bjorneberg, 1999 detail some of the deficiencies of hydrologic – and specifically, WEPP – modeling of the erosion/transport process when applied to furrow irrigation. In contrast to the hydrodynamic components of surface-irrigation models, sediment detachment and transport research is almost fundamentally empirical, and determinations suitable for hydrologic watershed models are sometimes not at all satisfactory in the surface-irrigation context. Typical hydrologic factors which impact on erosion-prediction capabilities, for example, include raindrop energy, flow rates which increase with distance downstream, lateral sediment influx from interrill flow, and, typically, concave landforms. In furrow irrigation, raindrops do not influence either entrainment or transport, flow rates decrease in the downstream direction, encouraging redeposition in downstream portions of a furrow; typically, there is no lateral influx of sediment, and the flow channels are essentially straight. Fernandez (1997), utilizing some of WEPP's basic premises, developed a complex model, tracking several size fractions through the phenomena of entrainment, transport and deposition, and documented satisfactory agreement with several Spanish soils. At USWCL, a simple erosion component was incorporated into SRFR, based on a single particle size representative of the mix in the furrow-bed, and with empirically determined critical shear and erodibility (Laflen et al, 1987; Elliot et al, 1988). Figure 2, drawn from a frame of the animation displayed by SRFR during a simulation (Strelkoff and Bjorneberg, 1999), illustrates a typical profile of the transport-capacity function and resultant sediment loads at one instant of time (61 minutes into the irrigation). The long region downstream, behind the stream front, in

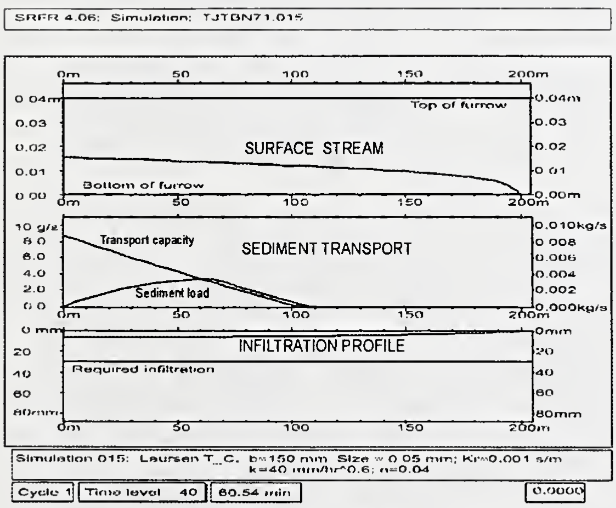

Figure 2. Frame of animated output of SRFR simulation – profiles of surface stream depth, sediment load and transport capacity, and infiltrated depths; time=61 min

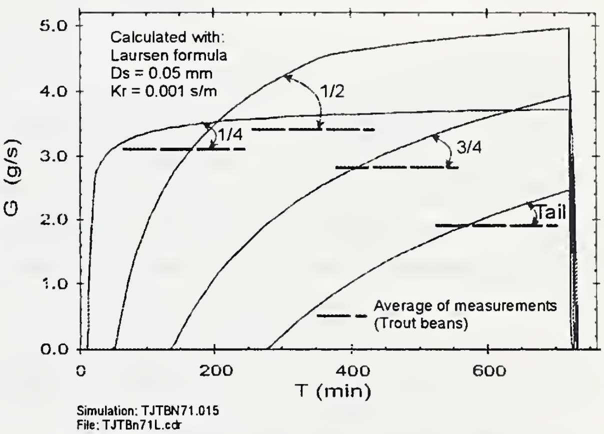

Figure 3 Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout bean data of Julky 1, 1994. Site specific Kr=0.001 s/m, τc=1.2 Pa, Laursen (1958) transport formula. (Strelkoff and Bjorneberg, 1999)

which the transport capacity and detachment are zero, testifies to the low flows there; boundary shear lies below the entrainment threshold. Upstream, the sediment load grows the fastest at the clear-water inflow, where transport capacity is a maximum and the existing sediment load zero. In the given instance, transport capacity is eventually exceeded, initiating deposition back onto the bed. Strelkoff and Bjorneberg (1999), utilizing the Laursen (1958) transport-capacity formula, and with the

representative particle size midrange in the field-measured mix, compared the simulation with field data obtained by Trout (1996) -- Fig. 3. In comparing several transport formulas, they found that the Yang (1973) and Yalin (1963) formulas greatly overestimated the capacity of furrow flow to carry sediment; consequently, deposition back to the lower reaches of the furrow is under-predicted. The Yalin formula provided the poorer predictions, corroborating the WEPP experiences of Bjorneberg et al. (1999). It is noteworthy that both the Laursen and Yang formulas were recognized by Alonso et al. (1981) as superior to that of Yalin, in predicting transport capacity in long channels, both in flumes and in the field. The Yalin formula, however, was selected for WEPP because it best predicted erosion in the very shallow rain-fed overland flow on concave hillsides (Foster, 1982).

While the agreement of SRFR simulations with measurements can be satisfactory, preliminary data shows that calculation with a single representative particle size is too sensitive to its selection. Furthermore, the most likely explanation for observed decreases in sediment flux across a section with time is a decrease in the supply from upstream due to armoring -- protection of smaller particles from entrainment by a gradually developing layer of larger ones above (Fernandez, 1997). Suggestions for treating the phenomenon were made by Borah (1982) and Borah and Bordoloi (1989), while Wu and Meyer (1979) suggested a reasonable way of apportioning total transport capacity amongst the size classes.

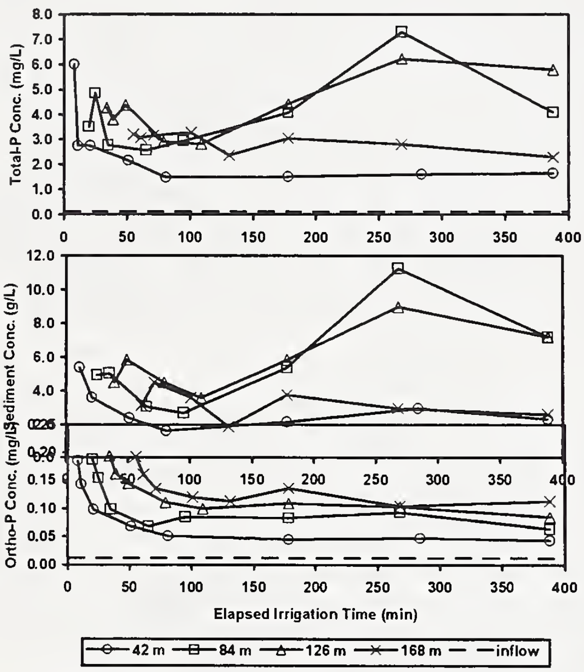

Figure 4. *Sediment, total-P and ortho-P concentration at four locations in an irrigation furrow (preliminary data – unpublished)*

Phosphorus (P): When furrow erosion is significant, affinity between P and soil-particle/aggregate surfaces ties the fate and transport of P in an irrigation stream to the sediments in transport. Several preliminary data sets on Portneuf silt loam (*Durinodic Xeric Haplocalcid*) have been collected at the NWISRL (ARS, Kimberly) for model development. Sediment, total-P and ortho-P concentrations along with water flow rate were measured with time and distance in a furrow (Fig. 4). Total-P concentrations closely follow sediment concentrations, while ortho-P concentrations are unrelated. Ortho-P concentrations decrease with time at a particular distance, but increase with distance at a given time.

Amongst the existing hydrologic/chemistry models, e.g., CREAMS (USDA, 1980), Opus (Smith, 1992), GLEAMS (Knisel, 1993), two approaches to modeling chemical constituents of runoff, Storm et al. (1988) and Ashraf and Borah (1992), appear the most promising for the purposes of the proposed study. In the first approach, the model of Storm et al. (1988) deals with uniform (lumped) field units and was designed for estimating rain-induced P transport from a field; in this case, the

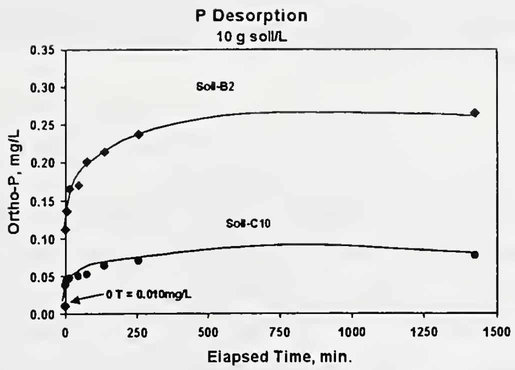

Figure 5. Phosphorus desorption for two soils (preliminary data from batch studies -- unpublished)

kinetic energy of the falling drops plays a role in P desorption (by influencing the thickness of the soil layer contributing P to solution). Storm et al. recognized a dynamic equilibrium in the runoff between soluble P and soil-bound P. In the transport of sediment-bound P, it is assumed that the distribution of P amongst the size classes of sediment is in proportion to their surface areas (confirming the need for a sediment transport model that tracks particle-size fractions in the flow). An empirical expression (Sharpley et al, 1981a, b, 1983), a power law in time, models the desorption of soluble P by the irrigation stream. The adsorption of P, on the other hand, can in many cases be assumed instantaneous. A common description of the equilibrium conditions of P reactions is the Langmuir isotherm (Tchobanoglous and Shroeder, 1985), which exhibits a limited adsorption capability, unlike, e.g., the Freundlich isotherm. A potentially significant factor in the chemical sub-models is the assumption of equilibrium isotherms in predicting reactions. Preliminary data collected at the NWISR Laboratory on reaction kinetics (Fig 5) may prove useful in judging the significance of those assumptions. NWISRL findings on the influence of soil chemistry on P in irrigation tailwater can be found in Westermann et al (2001).

The second hydrologic approach, the chemical component of the Ashraf and Borah (1992) model, is perhaps the most adaptable to the chemical aspects of furrow-water P modeling. This is a deterministic simulation of the entrainment (by rainwater) of P initially in the soil, partly in solution, and partly adsorbed to flow-entrained sediment, with the consequent P loading of the irrigation stream routed as kinematic waves to the field end and into the runoff. In this model, rainwater mixes with a mixing soil layer at the surface of the soil matrix, the degrees of interaction depending upon depth (*non-uniform* mixing -- Ahuja, 1982; Heathman et al., 1985). Simulation of this interaction is based on the following assumptions: -- (1) the mixing layer can be divided into depth increments, each increment homogeneous; (2) initial water content, porosity, and concentration in each soil increment are known; (3) all rainwater infiltrates into the soil during the early part of the rainfall event; (4) all pores participate, sequentially, in solute and water movement; (5) water entering the soil matrix mixes with soil water initially present in each increment and displaces it to the next increment, below; (6) except for adsorption and desorption, other chemical reactions are negligible; (7) dissolved and adsorbed phases in the furrow stream are in equilibrium, governed by a linear adsorption isotherm, simply a proportionality between concentration of solute and concentration of adsorbate, i.e., an empirical partition coefficient.

Thus, the result is a pair of advection equations in the respective concentrations in the furrow flow, one for dissolved P, and the other for adsorbed P, the two related by the partition coefficient. Source/sink terms for the first are described by the interchange of P between the pore water and the active soil bed layer, and between that layer and an assumed layer of the surface stream that

experiences complete mixing with the pore water. The second depends on the net entrainment of each particle-size class and the preference of P to adsorb to that class.

Objectives 3(c) and 4

Nitrogen -- Field work, modeling, and guidelines: Applying fertilizer through irrigation water (fertigation) can be a highly effective fertilizer management practice which offers certain advantages compared to conventional field spreading or soil-injection techniques -- reduced energy, labor, and machinery costs (Beth and Filters, 1981). A nitrogen management scheme of multiple fertigation applications with smaller amounts of N would reduce the need for large preseason or early-season applications, often associated with heavy N losses (Silvertooth et al., 1992; Watts et al., 1993). Fertigation is also more compatible with management tools such as residual soil nitrate assessment and in-season plant-tissue tests (Adamsen and Rice, 1995). In many cases, fertigation may be the only practical and economical method to apply additional nitrogen to surface-irrigated crops once the development of the crop precludes the use of machinery fertilizer applications. However, comprehensive guidelines for surface irrigation systems have not yet been adequately developed (Watts and Schepers, 1995).

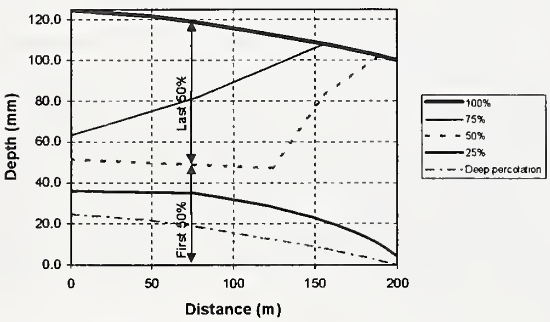

Figure 6. Cumulative infiltrated depth with distance, as contributed by the first 25%, 50%, 75%, and 100% of the applied water, and deep percolation with distance for a level basin irrigation system (preliminary simulation data -- unpublished).

Burt et al. (1995) provide a few general guidelines for fertigation in furrow and border-strip systems with tailwater runoff. One suggestion was to inject the fertilizer at a constant rate during the entire irrigation event. This recommendation assumes that the N-laden tailwater runoff will be blended with other water and reused in another field. Preliminary modeling studies have indicated that the timing and duration of fertigation applications during a surface-irrigation event play a critical role in determining the distribution of fertilizer in the field and the potential for nitrate movement to the groundwater (Watts et al., 1993; Playan and Faci, 1997). Deeper leaching of nitrogen can occur when using fertigation because the nitrogen, as NO_3, is already dissolved and moves with the water more readily than soil-applied fertilizer (Jaynes et al., 1992). The most effective fertigation practice appears to be strongly tied to the specific field conditions for the irrigation system, as demonstrated by the models of Playan and Faci (1997), Watts et al. (1993), and Boldt et al. (1994).

Santos et al. (1997), used simulation and field measurements to characterize nitrate movement under level-basin irrigation/fertigation. They established, for a particular sandy loam soil in Southern Portugal, that the transport and fate of NO_3-N was highly dependent on soil water movement, i.e., advection was governing the solute transport processes and dispersion was not important. If the irrigation uniformity is poor and if water freely flows off the end of the field, a large portion of the

applied N can be either leached below the root zone in the areas with excessive infiltration or transported in solution with tailwater runoff.

The importance in adjusting the timing and duration of a fertigation application during the irrigation event is illustrated theoretically for a level basin irrigation system (Fig. 6). Three options were considered -- injecting the fertilizer during the first 50% of the irrigation, the last 50%, or over the entire duration of the irrigation. To illustrate the problem, the curves identifying the source of infiltrated water in the basin were generated by a very simple advection model with zero longitudinal mixing. Furthermore, it was assumed that all water which enters the soil first is displaced downward by subsequent infiltration (in fact, some of the early infiltration can remain bound to the soil particles near the surface, while later infiltration flows around it, downward, through the remaining pore space). Consequently, the model shows that any deep percolation must contain the first water infiltrated.

The figure shows a relatively uniform infiltrated depth distribution following an irrigation; but water which enters the field in the early part of the irrigation, if not infiltrated *en route*, is pushed to the end of the field by later inflow and disproportionately infiltrates into the far end of the basin. This example illustrates a situation (closed basin) in which applying fertilizer during 100% of the irrigation event may be the best fertigation option. Injecting fertilizer during just the first 50% of the irrigation may result in poor N distribution uniformity throughout the basin, as suggested by the rather large differences between the infiltrated depths at the far end versus other areas of the basin after the first 50% of the irrigation water has infiltrated. Also, deep percolation N losses would be proportionately high, since all of the water in deep percolation is contributed by just the first 25% of the irrigation. In contrast, adding fertilizer during just the last half of the irrigation would result in too much N at the front end of the basin and too little at the far end, although there would be no N lost due to deep percolation. Applying fertilizer during 100% of the irrigation would result in a relatively even distribution of N in the root zone with a small portion of the total N leached with deep percolation (as represented by the area underneath the deep percolation curve). Quite different conclusions emerge with the same kind of simulation applied to sloping-border irrigation with tailwater runoff; in this case the smallest N losses are incurred with fertigation during the middle 50% of the irrigation. All of these conclusions are based on the aforementioned simple advection model, assuming, moreover, no spatial variability in soil properties; field verification is required.

We conducted a few fertigation experiments in level basins cropped to cotton, applying potassium bromide, a mobile tracer, during the whole 100%, the first 50%, and the last 50% of an irrigation event. The data have not yet been completely analyzed, but notable differences that appear in post-irrigation bromide distributions resulting from the different treatments suggest that significant progress can be made towards defining best fertigation management strategies in surface irrigation systems.

Results of CSREES-CRIS Search

A search of current and recent CRIS projects shows no research related to Objectives 1 and 2.

The sediment aspects of Objective 3 are addressed by research in ARS laboratories in West Lafayette, Indiana, (Implementation of Water Erosion Prediction Project, with L.D. Norton and D.C. Flanagan), Oxford, Mississippi (Evaluation of soil erosion and sediment transport processes on support of the DEC project with M.J. Romkens and C.V. Alonso), as well as Kimberly ID, with D.L. Bjorneberg and others. Nutrient constituents of irrigation water are addressed at Utah State University, Logan (Chemical application strategies for surface irrigation systems, with W.R. Walker and G.P. Merkley), and Univ Nebraska, Lincoln (Agrichemical control in irrigation runoff water from surface irrigated fields, with C.D. Yonts, R.G. Wilson).

Objective 4 is supported by three active non-ARS projects, two at Yuma AZ and one at Logan UT that are conducting research on fertigation in surface irrigation systems and one project completed in 1997 at Lincoln NE. We currently cooperate with the projects at Yuma AZ. In addition to the above fertigation projects, we also found two active CRIS projects and two inactive projects dealing with surface irrigation and nitrogen management. Our project is unique in that we are developing guidelines for injecting fertilizer into the water during operation of surface irrigation systems. This work will encompass a wide range of field conditions including a variety of soil types, irrigation inflows, and length of run and other aspects of irrigation system design.

APPROACH AND RESEARCH PROCEDURES

Objective 1 - Irrigation Software

Experimental Design

(a) Our current suite of stand-alone OS-based software products for one-dimensional surface-irrigation simulation (SRFR) and system design and management aids (BORDER, BASIN) will be reconfigured within a single shell, facilitating sharing of information. Bautista, Adamsen and Strelkoff will investigate alternative software development platforms on which to build this new software. Initial development will be Microsoft Windows but maximum portability to new PC operating systems is intended as these develop. Any such software needs to be object oriented. Appropriate ways will be sought for dealing with FORTRAN legacy code comprising the simulation and (interpolation-based) design engines. In addition, we will modify the SRFR simulation engine, as necessary, to allow it to interface with routines for erosion, sedimentation, and chemical transport. Whether the overall software shell development will be done in-house with current programmers or contracted out is yet to be determined.

In addition, Strelkoff and Clemmens will explore the possibility of linking the infiltration routines with a subsurface water and chemical transport model HYDRUS or UNSATCHEM (ARS, Riverside). This would allow use of soil physical data in determining infiltration rather than the current empirical approach. At a minimum, we will investigate SRFR's current options for treating the effect of furrow wetted perimeter on infiltration by comparing them with the more fundamental approach afforded by

the subsurface models which accept time-varying depths in a furrow as a boundary condition. A range of soil textures from sandy loam to clay loam will be used for several representative furrow shapes. Initially, these simulations will be run with a constant water level. Then, we will input varying water surface hydrographs that are representative of different surface irrigation conditions (e.g., different locations along the furrow, different flow rates, etc.). Field tests (Hunsaker, Adamsen) will be run at the Maricopa Agricultural Center to compare model and field results in conjunction with experiments described in Objective 3, below.

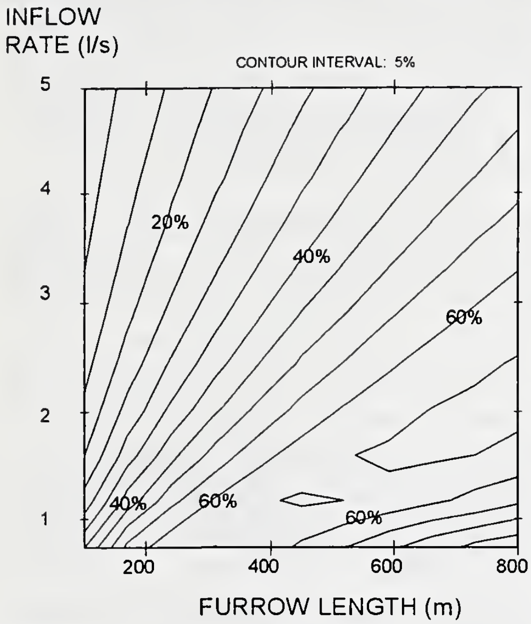

***Figure 7**. Potential Application Efficiency based on minimum depth equal to required depth (k = 30.1 mm/hr^a, a = 0.51, n = 0.05, W = 1 m, S_0 = 0.002, d_{req} = 80 mm)*

(b) Our current design software, based on a static database of previously run simulations, is limited in its range of applicability (even though expressing the results in non-dimensional form requires orders of magnitude less data). Simply extending this range would not be worthwhile because the designs would still be limited by the currently assumed border-strip geometry and two-parameter Kostiakov infiltration equation; and simulation and search procedures have not proven to be robust enough for novice users. So even with the ever increasing speed of personal computers, they still do not provide an adequate design approach. We recently developed a new approach that combines a very simple design approach with a limited number of simulations (Clemmens et al, 1998). This new approach mimics the approach in BORDER, where the performance parameters such as application efficiency are displayed as contours on a two-dimensional graph of two unknown design parameters (e.g., flow rate and field length). Under this approach, a single simulation is run at what we call an anchor point. The simulation results are used to tune the parameters of a simple design procedure which uses continuity, an assumed surface shape factor and a simplified recession relationship (Clemmens et al. 1998). This simplified design approach, with the tuned parameters, is used to calculate the performance parameters of interest (e.g., potential application efficiency) on a grid within the two-dimensional graph – through which the performance contours are drawn. An example is shown in Fig. 7 for furrow irrigation. The accuracy of the results varies with distance from the anchor point. Simulation at another point (perhaps as many as four) will be used to judge the accuracy of extrapolation or to allow interpolation. Further studies will determine the range over which extrapolation is acceptable. Within the software (Clemmens, Strelkoff, Bautista), the user will be able to execute a simulation at any point on the grid to determine the actual conditions there and note how far they deviate from the design solution presented. This new approach should be more robust than simulation-based search procedures and more accurate than the simplified design approach without tuning. It also has the advantage of allowing a wide variety of infiltration and roughness functions in addition to the full range of possible conditions for other input variables.

(c) A difficulty with the current software is selecting appropriate values for field infiltration and roughness coefficients needed as input to both simulation and design programs. A new software component for the SRFR suite will be generated to help users estimate these parameters from measured irrigation data (Bautista, Strelkoff, and Clemmens). It will be geared toward handling spatial and temporal variability. In addition, the measured irrigation data will be used, to the extent possible, to provide an evaluation of the irrigation event (e.g., application efficiency, distribution uniformity) based both on the measured data and on simulation with the estimated parameters.

The difficulty in developing such software comes from the variation in the type and amount of field data available. With research-level data, such parameters can be determined with good accuracy. However, typical surface irrigation evaluations by NRCS, mobile field labs, etc. provide a limited amount of data. Then assumptions have to be made, making the results potentially less accurate. Inaccurate parameter estimates can lead to inaccurate recommendations from the simulation and design programs. The proposed software will include routines for making parameter estimates that use the best available method (or methods) for the available data -- ranging from a minimum of data (inflow rate and advance times) to comprehensive research data (e.g., including water surface hydrographs). We have grouped the methods into four main categories, shown below. We are being assisted in evaluating these methods by the ASCE Task Committee on Soil and Crop Hydraulic Properties (chaired by Strelkoff). This group plans to publish guidelines for selection of methods based on the data-collection requirements of each method and on the expected accuracy.

Methods that measure only advance: • Shepard et al, 1993 (one-point method) • Elliott and Walker, 1982; Smerdon et al, 1988 (two-point method) • Clemmens, 1991 (direct inversion of ZI solution) • Walker and Busman, 1990 (simplex method minimizes differences between measured and simulated advance) • Bautista and Wallender, 1993 (Marquardt method minimizes differences between measured and simulated advance) • Clemmens and Keats, 1992; Clemmens, 1992 (Baysian estimation)	**Methods that measure advance, recession and enough water depths, y(x,t), to estimate the volume of surface water, $V_y(t)$ (volume-balance methods):** • Finkel and Nir (unstable); Maheshwari et al, 1988 (stable) • Gilley, 1968 (underestimates k, a for a complete irrigation) • Roth et al, 1974 (Fangmeier's method); Fangmeier and Ramsey (1978) • Strelkoff et al, 1999 (EVALUE, interactive selection of infiltration parameters; roughness follows)
Methods that measure advance and/or recession: • Clemmens, 1981 • Scaloppi et al, 1995 • Monserrat and Baragan, 1998	**Methods that measure advance and some water depths:** • Katopodes et al. 1990 • Valiantzas, 1994 • Playan and Garcia-Navarro, 1997 • Yost and Katopodes, 1998

Contingencies

The difficulty in filling vacancies for computer programmers is currently a significant problem. Student programmers often do not have the training and experience needed. We are considering contracting out portions of the software development as a necessity, although that can lack the desirable characteristics of long-term association with the project and retention of control by the scientists. If HYDRUS or UNSATCHEM is unable to adequately model soil infiltration or we are unable to link it with SRFR, we will explore other models. If simulation at a single point is not adequate for our design method, we will use more simulations to avoid extrapolation. There are such a wide variety of parameter estimation techniques available that we should be able to find appropriate methods for our software.

Collaborations

Necessary (within ARS) – Don Suarez, Rien van Genuchten, U.S. Salinity Laboratory on USSL soil water/chemistry flow models. Necessary (external to ARS) – Tom Spofford, National Water and Climate Center, NRCS, on relevance of research to NRCS field offices.

Objective 2 - Surface-Drained Level Basins

Experimental Design

Adoption of level basins with surface drainage by farmers is well ahead of our ability to provide design and operating recommendations. We have added the ability to remove applied irrigation water by surface drainage to the one-dimensional SRFR simulation software (Strelkoff et al 1998). A few field studies also have been conducted to provide preliminary data about the drain-back level basin systems, as used in the southwestern U.S. (Arizona, Colorado, Utah). Figure 8 shows a preliminary comparison between simulated and measured hydrographs with drainback for 2.5 ha flat-planted level basin (i.e., no furrows). Evaluation procedures followed the methods of Merriam and Keller (1978). In this example, the gross application depth (volume over field area) was 112 mm, while a volume representing 57 mm over the field surface drained off -- slightly more than half! While the fit of the data in Fig. 8 is good, the difference between the measured and simulated hydrographs represents 13 mm of applied water; 52 mm and 65 mm, respectively, remained on the field as measured and as modeled. We observed channeling of the flow that drained off the field surface, allowing more water

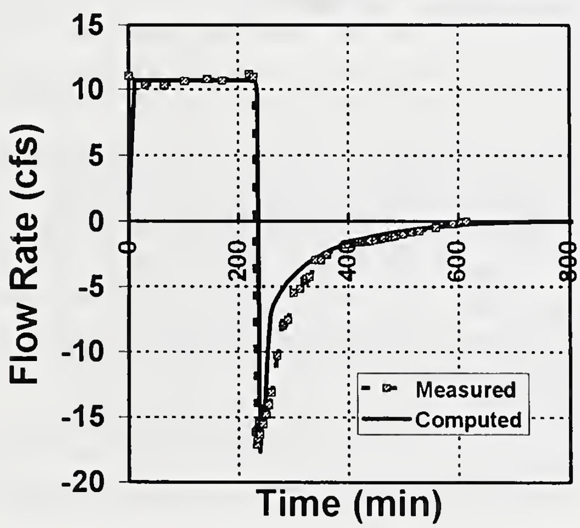

Figure 8. Measured and computed flow rate into and out of a 2.5 ha level basin with drainback. Eloy, AZ 9/3/98

to drain off than if flow had remained one-dimensional. Prior research had all been done under furrow irrigation, in which undulations in the furrow bottom elevation can be expected to reduce the predicted surface drainage (Dedrick and Clemmens 1988). We intend to conduct additional field studies on these drain-back level basins to further test our one-dimensional model and to determine its limitations.

Extensive field testing conducted in the late 1980s on drainage from irrigated furrows will be used to test the SRFR model routines for drainback (Clemmens, Strelkoff). Several dozen test furrows were run on two different soil textures; however, this preceded the addition of the drainback routines in SRFR (Strelkoff 1990). If necessary, we will conduct addition field tests on drain-back level basins with furrows (Hunsaker). We have half a dozen potential cooperators and will contact them as the need arises.

Once validated, we will conduct studies with the SRFR model to develop recommendations for (1) design and (2) operations. Initial design recommendations will be based on comparison to designs based on level basins without drainback according to the BASIN software. In particular, we will try to determine how to adjust the input to BASIN to give reasonable recommendations for drainback design, for example, increasing the depth of application entered as design input, since some fraction will drain off. Second, we will examine current operating criteria on when to cut off the water and start drainback or whether to hold water on the basin by allowing only partial drainback for a period of time (i.e, by holding a constant water level in the ditch and letting the inflow pass through to the next basin).

Clearly, even with the drain-back level basins, there is a need to model the two-dimensional nature of the flow to capture the influence of an undulating surface topography on drainage. With the grid of surface drainage channels (spin ditches) used in Louisiana, a two dimensional model is essential for modeling not only the irrigation and its drainage but also the drainage following significant rainfall events. Bautista and Clemmens will conduct field tests of irrigation events on these systems in Louisiana, both to evaluate their performance and to provide field data. Such evaluation will require more extensive data on field and water surface elevations than more traditional irrigation evaluations (Clemmens et al, 2001). In order to model this phenomenon (Strelkoff, Clemmens, Bautista), we will start with our existing two-dimensional model (Strelkoff et al, 2001) and assume that these spin ditches are one cell wide and just give them a lower elevation. This either creates a huge number of uniformly sized cells, or requires us to modify our computational routines to allow a non-uniform grid spacing. Another alternative is to model the spin ditches as a one-dimensional grid with side inflow and outflow. If these methods don't produce useful results, we will consider other models such as developed by Playan (1994) or Khanna (2000). Two-dimensional river flooding models are not adequate since they do not handle advance on a dry-bed, and they ignore flow over and through surface depressions because of computational difficulties (personal communication, Gary Feeman, West Consultants, Inc.).

Once a validated two-dimensional model is developed, Bautista and Clemmens will use it initially to assist farmers with proposed designs. They will conduct studies to provide preliminary design guidance, for example, spin-ditch spacing. For Louisiana and other areas in the humid South, this may be constrained more by the requirement for draining off rainfall than by irrigation concerns. We plan

to observe these basins during rainfall events to determine how long it takes for them to drain. The nature of the microtopography is expected to have a significant effect on drainage and thus on the modeling. Understanding the limits of this technology is important for avoiding failures that would slow adoption.

To date, information on the economic advantages of level basins, drainback level basins (Arizona) and grid-drained level basins (Louisiana) is all anecdotal (e.g., Clemmens 2000). Results in Arizona generally suggest conversion to level basins is economical only if water costs are high or yields increase by at least 10%. Such yield increases have been reported in several studies (Bathurst 1988, Galusha 1986). Conversions to drainback level basins are less expensive and have shown payback in one to two years. In Louisiana, yield increases of 20 to 40% have been reported over traditional furrow irrigation perhaps due to land leveling. Data on the systems in Louisiana have been insufficient either to determine the cause of the yield changes or to conduct an economic analysis of the new systems. Bautista will collect sufficient information on the costs and benefits of systems which have been converted so that an economic analysis can be performed. Interviews with growers and irrigators will ensure that the recommendations are compatible with farming practice and will be viewed as leading to effective, safe approaches to farm profitability and sustainability. As these studies unfold, we will contact appropriate extension personnel in Louisiana and neighboring states to assist us in the analyses. We also plan to establish links with the ARS station in Stoneville, Mississippi, which is currently hiring an irrigation engineer.

Contingencies

Development of a useful two-dimensional model could fail due to scale problems (i.e., 0.2 *m*-wide drainage channel versus a 50 *m*-wide field surface). In this case we may explore a multiple furrow model partially developed but on hold. Field evaluations rely on farm cooperators. We have several in Arizona and Louisiana and can find alternates if current cooperation does not continue.

Collaborations

Necessary (ARS) – New hire irrigation engineer, Stoneville MS.
Necessary (external) – Farm owner, manager of test fields; Tom Spofford, NWCC, Mike Sullivan, NRCS National Water Management Center, Little Rock AR on local needs and practical applications; distribution and training.

Objective 3 - Fate and transport of sediment, phosphorus, and nitrogen

Experimental Design:

MODELING

Erosion: Strelkoff will expand the current single particle-size erosion component of our surface irrigation simulation model (SRFR) to accommodate mixes of particle sizes, in the furrow bed and in the flow. These are not the same, with the mix in the flow typically finer than the mix in the bed (hence, phosphorus enrichment in the irrigation tailwater). The mix of particle sizes in the furrow bed

will be measured with relatively coarse subdivisions, either three (% sand, silt, and clay) or five, in which fine sands and fine silts are separated out, depending on measurement capabilities of a cooperating project at Kimberly, ID (discussed below, under the *Field Studies* subheading). With mean, standard deviation, and skew of the distributions measured, we can replace the coarse subdivisions by a continuous distribution with the same characteristics to enter into the model. We plan to apply the Borah et al (1982) concept of selective entrainment to each location along a furrow bed of assumed well-mixed particles: the smallest go first, and then larger, and so on, until the transport capacity at that section is filled. The largest particles may well stay behind, shielding smaller ones beneath from detachment. We will apportion the total transport capacity amongst the entrained size fractions in accord with Wu and Meyer (1989). Here, the fraction of total transport capacity allocated to a particular particle size in the mixture is governed by a weighting factor, namely, the transport capacity for a homogeneous soil composed of the given size, relative to the sum of such transport capacities for all the fractions carried by the flow. When transport capacity for any size is exceeded, the deposition rate will be based on the pertinent fall velocities, using the Rubey formula (Simons and Senturk, 1992). From these processes, the sediment loads and concentrations at selected points along the furrow will be output, as tables and graphs, as will the profiles of erosion and depositions along the furrow length. This output can be used to judge the relative merits of one design or management procedure over another.

Phosphorus: Strelkoff and Clemmens will add a component to SRFR to simulate fate and transport of phosphorous (P). P transport is primarily through sorption to soil surfaces with more sorption per unit mass of soil on smaller soil particles. Thus the planned full particle size-distribution erosion component in SRFR is essential. In addition, P desorbs from the soil and can be transported in the liquid phase. Initial studies of this desorption process will be used to develop relationships for modeling the advection and dispersion of ortho-P in the flowing water. Batch studies from a cooperating project at Kimberly ID (*Field Studies* subheading, below) will be used to develop desorption relationships. We plan to fit a first-order reaction formula to the measured data in which the rate of desorption is dependent upon the difference in concentrations, replacing Sharpley's et al (1981a,b) power law for cumulative desorption with time. This desorption *rate* is required in the simulation algorithm.

When the soil is eroded from the soil surface, we will assume P in equilibrium between the solid and liquid phases, i.e. an equilibrium version of Ashraf and Borah (1992). We will evaluate the suitability of this approach relative to that used for P desorption from the surface so that they are compatible. If necessary we will implement fully non-linear or time-dependent desorption of P from the entrained sediment. Furthermore, the transport in the irrigation stream of dissolved and adsorbed P will be assumed by advection alone in a kinematic wave-like formulation. Longitudinal dispersion arising from the interplay of vertical turbulent diffusion and the mean-velocity distribution in the vertical will be ignored, in keeping with standard practice in modeling sediment transport. To ensure as little numerical dispersion as possible, numerical solution of the advection equations will be undertaken by the piecewise method of characteristics on SRFR's rectangular net in the x-t plane with cubic-spline interpolation along the known time line (Komatsu et al, 1997). This maintains compatibility with the SRFR grid used for surface hydraulics and avoids dissipative effects that are strictly numerical stemming from use of a rectangular grid as commonly used for kinematic-wave solutions.

The suitability of the above modeling approach will be evaluated with data from the field studies conducted by a cooperating project at Kimberly ID (*Field Studies* subheading below).

The simulations will lead to SRFR output tables and graphs of concentrations and total P-load hydrographs at selected points along the irrigation furrow, in particular the loading in the tailwater. This output is designed to help guide development of design and management practices that take total P loading into account.

Nitrogen: Nitrogen (N) transport will be added to SRFR after sediment and P transport have been verified (Strelkoff, Adamsen, Clemmens). In this case, the N is applied in the irrigation water (fertigation). Initially, N will be considered completely nonreactive with the soil and move only with the water flow. Complete transverse mixing in the irrigation stream will be assumed while longitudinal advection and dispersion will be modeled. Dispersion coefficients will initially be based on values from the literature. We will investigate ARS software (HYDRUS and UNSATCHEM) developed at other locations for modeling the subsurface transport and fate in response to the concentration and water-depth histories at the surface. Field studies of N fertigation practices, described below, will be carried out to develop an understanding of various practices on the fate of applied N under different application regimes and different surface irrigation systems. These studies will provide both a basis for preliminary recommendation and data for model validation. Specifics of the modeling approach will depend on results from the P modeling described above.

FIELD STUDIES

Erosion, Phosphorus: Field measurements of irrigation water flows and sediment and phosphorus concentrations, as well as laboratory batch studies of P/soil/water reactions, will be undertaken by our cooperating institution, ARS, Kimberly, ID., under (old) CRIS Project Numbers, 5368-13000-004-00D (Irrigation Management to Reduce Erosion and Improve Water Use Efficiency) and 5368-12130-007-00D (Water Quality Protection in Irrigated Cropping Practices and Systems).

Nitrogen: A series of field experiments will be conducted by Hunsaker and Adamsen to determine the distribution and potential leaching of nitrogen applied in the irrigation water. Initially, these experiments will be conducted at each of 10 proposed field sites as listed in Table 1, which represent several types of surface irrigation systems and a range of soil types. Each fertigation experiment will include four treatments and three replications for a total of 12 field plots per site. Plots will be at least 6.5 m wide and as long as the length of run of the field. The four fertigation treatments proposed are (1) fertilizer injection over 100% of the irrigation, (2) just the first half, (3) just the middle half, and (4) just the last half of the irrigation.

Table 1. Proposed field sites for fertilizer application studies.

System type	Soil types	Location	Crop
Level basin, unfurrowed	sandy loam	Maricopa, AZ	wheat
	clay loam	Maricopa, AZ	wheat
Level basin, furrowed	sandy loam	Maricopa, AZ	cotton
	clay loam	Maricopa, AZ	cotton
Sloping border without runoff, run less than 275 m	sandy loam	Coachella Valley, CA	small grain
Sloping border without runoff, run greater than 360 m	sandy loam	Coachella Valley, CA	small grain
Sloping border with runoff	silt loam	Coachella Valley, CA	small grain
	cracking clay	Imperial Valley, CA	small grain
Sloping furrows with runoff	sandy loam	Casa Grande, AZ	cotton
	silt loam	Coachella Valley, CA	corn

Preliminary data will be collected at each site to determine field conditions – field geometry, infiltration and roughness, and soil texture. SRFR will be used to determine the application time and flow rate needed for the border width used to achieve the best water application uniformity. These will be used for each irrigation event at the site and adjusted as needed for specific conditions at the time of irrigation.

During experiments, nitrogen fertigation will be simulated by injecting potassium or calcium bromide into the irrigation water stream. Bromide was selected because it simulates nitrate well and is present in low concentrations in the environment, making it detectable as a tracer. In addition, bromide is conserved biologically so that a mass balance can be calculated. While the most common form of fertilizer used for injection is urea ammonium nitrate solution, it is the nitrate dissolved in the irrigation water that poses the greatest immediate threat to the environment.

Prior to each simulated fertigation event, soil samples will be taken from the field. Samples will be taken in the non-cropped turn around area at the head of the field if one exists, at the beginning of the cropped area, and then at five evenly spaced locations between the top of the field and the end of the run, resulting in a maximum of seven sample locations in each plot. When the experimental site is furrowed, a sample will be taken from two adjacent beds and from a wheel and non-wheel furrow bottom at each sampling location. When the site is flat, unfurrowed, two samples will be taken from an area not affected by wheel compaction and two samples from wheel tracks at each sampling location. Soil samples will be taken to a depth of 1.2 m and divided into 5 depths, 0 to 0.15, 0.15 to 0.30, 0.30 to 0.60, 0.60 to 0.90 and 0.90 to 1.2 m. A complimentary set of samples will be taken as soon after the irrigation event as possible. Plant samples also will be taken after the irrigation for analysis of bromine. This data should amply show the spatial variability of fertilizer distribution.

Basic irrigation performance data also will be collected for each event (Merriam and Keller 1978). In addition, water depths will be measured directly with rulers placed in the field at selected locations.

Water samples will be taken every 15 minutes from the input water stream below the injection point and when runoff occurs from the runoff stream.

Soil samples will be analyzed for bromide and gravimetric water content and nitrate. Samples will be kept in a field-moist condition from sampling until gravimetric water content measurements can be made. During transport from the field to the laboratory, samples will be stored on ice to prevent nitrification. Sub-samples will be taken for soil moisture contents. Nitrate and bromide will be extracted from the samples with a 1:1 weight to volume water extraction. Plants will be analyzed for bromine after acid digestion of the plant material. Nitrate determinations of soil extracts and water samples will be made with an autoanalyzer using cadmium reduction (Adamsen et al., 1985) and bromide determinations on soil extracts, water samples, and plant digestions will be made with an autoanalyzer using a fluorescein dye method (Marti and Arozarena, 1981).

Distribution of bromide will be compared to the infiltrated water depth distribution from each fraction of the irrigation to determine the degree of mixing that occurred between fractions and the degree of variability that exists. The estimates of mixing between fractions will be used to help validate the N fate and transport component for SRFR, proposed above. Additional field studies will be conducted as needed to validate this aspect of the model.

Contingencies

In the event the proposed computational algorithms fail to yield satisfactory predictions, the program of field and laboratory measurements of sediment movement and chemical exchanges will provide an empirical basis for alternate algorithms. The proposed project does not deal with the movement of water and chemicals below the soil surface, and the results could be limited by not properly modeling this aspect. However, other scientists, both within and outside ARS, have such capabilities (e.g., as noted at ARS Riverside) that can be used to significantly enhance this project. Field heterogeneity and preferential flow can often cause significant differences in infiltration rates during irrigation, which may produce misleading results of bromide distributions and irrigation uniformity during some of our experiments. Results may be inconclusive due to excessive heterogeneity.

Collaborations

Necessary (within ARS) – Dale Westermann and David Bjorneberg (ARS Kimberly) to collect sediment samples in the field and analyze for physical and chemical-exchange properties. Don Suarez and Rien van Genuchten (ARS Riverside) on modeling water and chemical movement below the soil surface. Necessary (external to ARS) – T. Spofford, NWCC (NRCS).

Objective 4 - Guidelines for water and fertilizer application

Experimental Design

Hypothesis: Timing and duration of fertilizer injection during surface irrigation events affects the fate and uniformity of nitrogen fertilizer. The appropriate timing and duration of fertilizer injection is affected in predictable ways by many factors including irrigation system design, infiltration rates

which are in turn affected by soil type, tillage, frequency of irrigations, and sealing of the soil surface as a result of previous irrigations. The investigations will be performed primarily by Hunsaker, Adamsen, and Clemmens.

The results of the field experiments should provide an estimate of the uniformity of fertilizer applications in surface irrigation system when the fertilizer is added to the irrigation water during different periods of the irrigation. The experimental design encompasses a range of soil types and common designs of surface irrigation systems. The preliminary data set will be robust enough to provide basic guidance to farm managers and consultants for BMPs for fertigation with surface irrigation systems. These guidelines will be disseminated to Cooperative Extension and NRCS field offices as they become available as well as published in refereed scientific journal articles.

The simulation model will be used to conduct a more systematic study of the preliminary recommendation developed from the field studies. This will allow us to examine tradeoffs in the design and operation of surface irrigation systems, including chemigation, and to develop recommendations, taking into account prevalent farmer attitudes and practices. The scope of these studies depends on the results of the field studies and the capabilities of the simulation model to reproduce those results.

Contingencies

The development of comprehensive fertigation recommendations relies on our being able to model the movement of nitrogen under surface irrigation. Recommendations can be made without this, but will be less generally applicable.

Collaborations

Necessary (within ARS) – None. Necessary (external to ARS) – T. Spofford, NRCS.

NATIONAL COLLABORATION

All four NP201 Water Quality and Management Policy Initiatives are supported by this research. USWCL's contribution to the Initiatives on TMDL Monitoring and Research and Coastal Water Quality Protection relates to the edge of field and other offsite contributions of surface irrigation to sediment, phosphorus, and nitrogen in the watershed (Problem Areas 2.6, 3.1, 3.4, 3.7). The initiative on Drought and Water Scarcity is addressed in connection with Problem Area 2.3. The Water Resources Models, Decision Support Tools and Information Databases National Initiative, is supported by USWCL's development of surface irrigation software. ARS laboratories outside Phoenix address these initiatives primarily at the watershed scale and in connection with irrigation sprinkling and microirrigation systems. Deliverables stemming primarily from the Phoenix location are validated models, software assisting in design and management of surface irrigation systems, and recommendations on water and nutrient applications in surface irrigation, as detailed in the above sections. Collaborative efforts are currently ongoing with Spofford, NRCS Water and Climate Center, Portland OR to ensure the relevance of our program to NRCS field applications, and with Westermann and Bjorneberg, ARS Kimberly ID on soil erosion and P transport under surface

irrigation. We anticipate expanded cooperation with Suarez and van Genuchten, ARS Riverside CA on modeling water and nitrogen movement in soils under surface irrigation. We hope to establish cooperative relationships regarding level basins in humid areas with the irrigation engineer to be hired at ARS Stoneville MS to complement those established with Sullivan and Carman at the NRCS National Water Management Center in Little Rock AR.

PHYSICAL AND HUMAN RESOURCES

The USWCL has full time staff and laboratory facilities to conduct a wide variety of agricultural research. In addition to high speed LAN and Internet connections, the Lab's PCs are well-equipped with current word-processing, spreadsheet, graphics, presentations, and development software. A soils laboratory is available to conduct, e.g., soil particle size analysis. Soil samplers, neutron scattering, and TDR equipment is available for field analyses. An analytic chemistry lab is available for analyses of water and soil samples. An electronics shop, staffed with an electronics engineer, is available for development and repair of electronic instruments as needed. The Maricopa Agricultural Center, The University of Arizona, is available for nitrogen field work. Field and laboratory batch studies on phosphorus will be conducted by a collaborating facility, the ARS NWISRL, at Kimberly ID.

In addition to the named category I scientists, three Physical Science Technicians (2.8 FTE), a temporary Computer Specialist and Computer Assistant will be employed in this research. In addition, a temporary category II (Post-Doctoral Research Scientist, 1.0 FTE, GS-12 term appointment) position is in the process of being filled. Though the position is funded extramurally, much of the incumbent's responsibilities will lie within the purview of this project.

MILESTONES AND EXPECTED OUTCOMES

Expected outcomes include an extended surface-irrigation-simulation model (SRFR) with fate and transport of water, sediment, phosphorus, and nitrogen in the irrigation stream. The simulation model is to be part of an integrated user-friendly suite, SRFRSuite, including design/management aids and field-evaluation components. We expect to publish guidelines for the design and management of surface-drained level basins and for fertigation management in surface irrigation.

Milestone Timeline

Research Component	End of year 1	End of year 2	End of year 3	End of year 4	End of year 5
SRFR Suite: hydraulics	Select platform languages	Complete field-evaluation component	Complete furrow-design component		Complete SRFR Suite
Surface-drained level basins		Complete field studies of GSDLB (grid-supplied & drained level basins)	Guidelines for DBLB (drainback level basins)	Complete modeling of GSDLB	Guidelines for design and management of GSDLB
SRFR constituent simulation	Complete sediment transport component	Complete phosphorus fate and transport	Validate and calibrate sediment and phosphorus models	Complete N transport in the irrigation stream Couple to soil-water/chemistry model	Validate and calibrate nitrogen model
Nitrogen fertigation management		Field studies of nitrogen uniformity and efficiency completed	Preliminary guidelines on fertigation with surface irrigation issued		Final guidelines on N fertigation with surface irrigation

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ENVIRONMENTAL
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PLANT DYNAMICS
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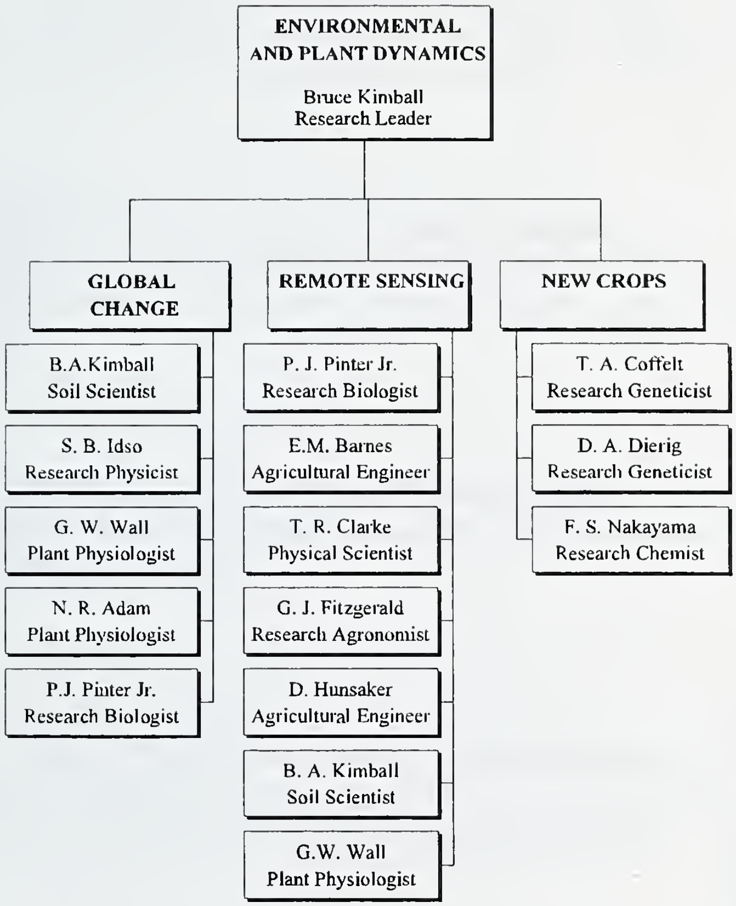
E&PD Organization

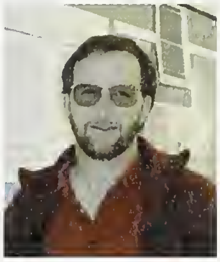


Mission

The Environmental and Plant Dynamics (E&PD) Research Group seeks to develop optimum resource management strategies for meeting national agricultural product requirements within the context of possible changes in the global environment. There are three main research thrusts: The first is predicting the effects of the increasing atmospheric CO_2 concentration and climate change on the yield and water use of crops in the future. The second thrust seeks to improve agricultural water management utilizing remote sensing approaches for observing plant conditions and biophysical processes which are amenable to large scale resource monitoring using aircraft- and satellite-based sensor systems. The third research thrust is to develop new industrial crops with unique high value products and lower water requirements for commercial production within the context of changing environments.

E&PD RESEARCH STAFF

NEAL R. ADAM, B.S., M.S., Ph.D., Plant Physiologist
Research regarding physiological, biochemical and molecular responses of wheat to CO2 enrichment in FACE crop canopy experiment. Establish protocol for enzyme activity assays, SDS-PAGE and other biochemical procedures on leaf samples. Design and implement data collection and processing tools.



EDWARD M. BARNES, B.S., M.S., Ph.D., Agricultural Engineer
Remote sensing applications for farm management; consideration of approaches that integrate remotely-sensed measurements with crop growth models and decision support systems.

THOMAS R. CLARKE, B.A., Physical Scientist
Remote sensing for farm management, thermal and optical radiometry, and instrument calibration.

TERRY A. COFFELT, B.S., M.S., Ph.D., Research Geneticist-Plants
Breeding, genetics, and germplasm evaluation of new crops--guayule, lesquerella, and vernonia; development of acceptable production practices.

DAVID A. DIERIG, B.S., M.S., Ph.D., Research Geneticist-Plants
Breeding, genetics, germplasm collection and evaluation of new industrial crops with unique, high-value products, including lesquerella, vernonia, and guayule.

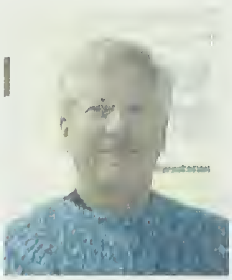
GLENN J. FITZGERALD, B.A., M.S., Ph.D., Research Agronomist
Application of geospatial technologies to site specific farming, multispectral and hyperspectral remote sensing for detection and identification of plant stress and anomalies.

DOUGLAS J. HUNSAKER, B.S., M.S., Ph.D., Agricultural Engineer
Effects of soil and irrigation spatial variability on crop water use and yield in large irrigated fields; level basin irrigation design and management procedures for applying light, frequent water applications to cotton; CO2 effects, in particular, of evapotranspiration in the free-air CO2 enrichment (FACE) environment; evaluation of water requirements and irrigation management of new industrial crops--lesquerella and vernonia.

SHERWOOD B. IDSO, B.S., M.S., Ph.D., Research Physicist
Effects of atmospheric CO_2 enrichment on biospheric and climatic processes.

BRUCE A. KIMBALL, B.S., M.S., Ph.D., Research Leader for E&PD and Supervisory Soil Scientist
Effects of increasing atmospheric CO_2 and changing climate variables on crop growth and water use; free-air CO_2 enrichment (FACE), and CO_2 open-top chambers and greenhouses; micrometeorology and energy balance; plant growth modeling.

FRANCIS S. NAKAYAMA, B.S., M.S., Ph.D., Research Chemist
New crops such as guayule (for latex rubber and resin), lesquerella (hydroxy fatty acid) and vernonia (epoxy fatty acid); including extraction and analytical techniques and by-product uses for the various components; Editor-in-Chief of Industrial Crops and Products, an International Journal.



PAUL J. PINTER, JR., B.S., M.S., Ph.D., Research Biologist
Applications of remote sensing technology to management of agricultural resources and research in plant sciences; effects of elevated CO_2 on biophysical properties of plants.

GERARD W. WALL, B.S., M.S., Ph.D., Plant Physiologist
Derivation of experimental databases to quantify growth, development, and physiological response of agronomic crops to full-season CO_2 enrichment; development of deterministic and stochastic digital simulation models of the soil-plant-atmosphere continuum in response to a CO_2 enriched environment.

AGRICULTURAL PRODUCTIVITY AND WATER USE: EFFECTS OF GLOBAL CHANGE

Bruce A. Kimball, Supervisory Soil Scientist
Sherwood B. Idso, Research Physicist
Gerard W. Wall, Plany Physiologist
Paul J. Pinter, Jr., Research Biologist
Neal R. Adam, Plant Physiologist

PROJECT SUMMARY

We propose to conduct global change research over the next three years with the following objectives: (1) Determine the long-term effects of elevated CO_2 on the physiology, growth, wood production, fruit yield, fruit nutritional quality, and water use efficiency of sour orange trees, as well as its effects on soil structure and carbon. This is a continuation of an ongoing open-top chamber experiment started in 1987, which is the longest such continuous CO_2-enrichment experiment ever conducted. (2) Assess likely impacts of global change on the productivity of agricultural crops via synthesis and integration of existing large accumulated experimental data base plus additional crop growth modeling. (3) Determine effects of elevated CO_2 on the physiology, growth, yield, N_2-fixation, persistence, and soil carbon sequestration of alfalfa using the free-air CO_2 enrichment (FACE) approach. This experiment is the logical follow-on to prior such FACE experiments on cotton, wheat, and sorghum conducted at Maricopa, AZ. (4) Determine effects of elevated CO_2, water supply, and grazing pressure on productivity, shrub-grass competition, carbon sequestration, and water relations of the piñon-juniper rangeland ecosystem, also using the FACE approach. This new project, called Carbon Exchange and Sequestration in Arid Regions (CESAR), would utilize CO_2 from a huge geologic source within this ecosystem, and it would involve a large consortium of universities, ARS, private industry, and others. Achieving Objectives 3 and 4 is contingent upon obtaining outside funding.

OBJECTIVES

1. Determine the long-term effects of elevated CO_2 on the physiology, growth, wood production, fruit yield, fruit nutritional quality, and water use efficiency of sour orange trees, as well as its effects on soil structure and carbon sequestration beneath the trees.

2. Assess likely impacts of potential global change on productivity of agricultural crops via synthesis and integration of large accumulated experimental data bases.

[Note: Objectives 3 and 4 are contingency plans dependent upon obtaining outside funding.]

3. Determine effects of elevated CO_2 on the physiology, growth, yield, N_2-fixation, persistence, and soil carbon sequestration of alfalfa.

4. Determine effects of elevated CO_2, water supply and grazing pressure on the productivity, shrub-grass competition, carbon sequestration, and water relations of the piñon-juniper rangeland ecosystem.

NEED FOR RESEARCH

Description of the Problem to be Solved

1. Sour orange: Whether enough carbon can be sequestered in the boles of tress and in the soil beneath them to significantly slow the rate of rise of atmospheric CO_2 concentration is an important question facing global change research, as are the implications of the ongoing CO_2 rise for human nutrition. *Sour orange* represents such long-lived woody species, which is being studied to determine (1) whether an initial CO_2-induced enhancement in wood and fruit production will be maintained over a tree's life span, (2) whether quality of wood and fruit will change, and (3) whether increases will occur in soil carbon storage beneath the trees.

2. Synthesis and Integration: Policymakers often have difficulty perceiving principles from the vast array of facts before them, so a common refrain is that the products of scientific research are "data rich and knowledge poor." Currently, about 2 papers are being published every 3 days about the effects of CO_2 and other environmental variables on agricultural crops, from which more definitive knowledge about global change effects on agriculture needs to be synthesized. Furthermore, available assessments may be suspect. The Inter-governmental Panel for Climate Change is now writing its third major assessment of likely impacts of global change on agriculture (as well as many other facets of world society), but most of the predictions are based on simple plant growth models which ignore some important plant processes (IPCC, 2001).

   Four simple models (Tubiello et al., 1999; Jamieson et al., 2001) were able to simulate the responses of wheat to elevated CO_2 interacting with soil water and soil nitrogen supplies as observed in our free-air CO_2 enrichment (FACE) wheat experiments. Nevertheless, such simple models as tabulated by the IPCC (2001) cannot address some important aspects of plant growth responses to elevated CO_2. For example, they "grow" the crops at air temperature rather than at the crop's own temperature; yet, we have shown that elevated CO_2 causes wheat canopies to warm 0.6 to 1.2°C above air temperature due to the direct effects of the elevated CO_2 on the plants' stomatal apertures (Kimball et al., 1992, 1995, 1999). Such warming would be in addition to any global warming of air temperature, and it could cause similar consequences, such as changes in yield and major shifts in optimal production regions of crops. A second effect that is not adequately addressed by simple daily-time-step models is that plants make their photosynthate during daytime, yet they continue to translocate material and grow at night. Therefore, daily temperature patterns may be very important in determining plant responses to elevated CO_2. One prediction of general circulation models is that night temperatures are likely to warm more in the future than daytime temperatures (Collatz et al., 2000; Easterling et al., 1997; Hansen et al., 1995). Therefore, another generation of assessments needs to be done -- with detailed process-oriented models capable of simulating all known effects of elevated CO_2, as well as of other interacting environmental variables, on crop physiology, growth, yield, carbon sequestration, and water relations.

3. Alfalfa: Alfalfa is a perennial deep-rooted legume crop that has the potential to respond to elevated CO_2 with deep sequestration of soil carbon, even at low soil nitrogen and thereby slow the rate of rise of the atmospheric CO_2 concentration. It is an important forage crop in the U.S. (24 million acres; 4th in acreage behind corn, wheat, and soybeans; USDA, 2000) that grows well in Arizona. Specific scientific reasons to focus on alfalfa are: (1) being deep-rooted, alfalfa can sequester carbon at deeper depths below the plow layer where it may be able to be stored for much longer periods, (2) being perennial, alfalfa grows the year around, so the interaction between elevated CO_2 and temperature can be studied, and (3) being a legume, the effects of elevated CO_2 on nitrogen fixation can be examined, as can the importance of nitrogen for C sequestration.

4. Piñon-juniper: Piñon-juniper is an expansive ecosystem whose character may be changed by global change. This vast mid-elevation ecosystem serves as rangeland for substantial cattle production and watershed catchment for much of the Western U.S. It contains more than a dozen National Parks and Monuments, is home to numerous Native American groups, has a history of varied natural resource management (fire suppression, logging, grazing), and is under great development pressure from surrounding regions (Wilkinson 1998). Little research has addressed biosphere-atmosphere interactions of this region, yet paleoecological studies and climate change models indicate this region may be highly sensitive to global change (Cole,1985; Nielson, 1995; Grissino-Mayer et al., 1997). Land use (fire suppression, grazing) has had widespread impacts on this region (Fleischner, 1994; Brown and McDonald, 1995; Moore et al., 1999), yet we do not understand the implications of these activities for C exchange and sequestration, nor the nature of their interaction with atmospheric and climatic change. Insect outbreaks associated with climate change appear to be increasing (Walker et al., 1998). Their impacts on ecosystem C fluxes and sequestration can be significant but are little understood in arid regions. Of the region's major vegetation types, the piñon–juniper woodland is the third most extensive in the continental U.S. Therefore, there are several reasons to determine the effects of elevated CO_2 and other interacting environmental variables on this important ecosystem.

Relevance to ARS National Program Action Plan

The project is relevant to all components. While the primary emphasis is on determining and assessing the impact of global change on *agricultural ecosystems* and to develop strategies for adaptation, this research inherently involves studying all aspects of *carbon cycling* from photosynthetic carbon assimilation to soil carbon sequestration, the latter of which can mitigate the rate of global change. Production of *trace gases*, such as N_2O, will also be addressed. In addition, the influences on surface energy balance and evapotranspiration will be assessed, thereby contributing to the *water cycle* component.

Potential Benefits

The main benefit will be an enhanced ability to prepare for potential global change. Knowing the probable impacts of global change on crop production and water use in each region will give researchers and growers the incentive to develop strategies for coping with problems and maximizing

benefits, as well as for sequestering carbon to mitigate the rate of global change. The growth models developed as part of this research should prove to be useful tools for developing such strategies.

Anticipated Products

Scientific publications will be produced that describe, as well as synthesize and integrate, the effects of elevated CO_2 and interacting environmental variables on plant physiology, growth, yield, light use efficiency, carbon sequestration, and water use of crops and rangeland for various regions and global change scenarios. Process-based plant growth models that have been more perfected and validated than currently exist will also be products of this research.

Customers

Other agencies, such as the Department of Energy and Environmental Protection Agency, need the information to set policy regarding carbon storage credits, energy sources (i.e., coal versus nuclear), CO_2 emissions (whether to tax or not), and land use (reforestation). Agricultural policymakers will also use the information to formulate resource conservation plans for the next Farm Bill, especially if there is a "green payments" program that encourages carbon sequestration. And, of course, farmers eventually will use the information.

SCIENTIFIC BACKGROUND

1. Sour orange trees:

A search of the CRIS system for "global change" or "CO_2" or "carbon dioxide" revealed that 198 projects are coded for work on these topics within ARS and that another 547 are also outside of ARS. However, only about 40 pertain to assessing the impact of global change, especially of elevated CO_2, on agricultural ecosystems. CO_2 enrichment research is being conducted at the ARS Gainsville, Beltsville, Auburn, Temple, Raleigh, and Ft. Collins locations. Some of the non-ARS projects were free-air CO_2 enrichment (FACE) projects on desert in Nevada and on trees in Wisconsin and North Carolina, and the latter will be discussed shortly. However, our long-term study on sour orange trees appears to be unique.

Beyond the CRIS system, there have been many reports of the growth responses of trees to atmospheric CO_2 enrichment; however, the vast majority of them have been of relatively short duration. In a recent review of the literature, for example, Idso (1999) evaluated the results of 180 such experiments, finding that only two of them extended beyond four years duration. In addition, all of the short-term studies (three years or less) dealt with trees growing in different types of rooting media in containers located in growth chambers or greenhouses, as opposed to the undisturbed soil of the natural environment. Because of these protocol deficiencies, these latter studies are clearly incapable of answering important questions related to carbon sequestration in trees and soils.

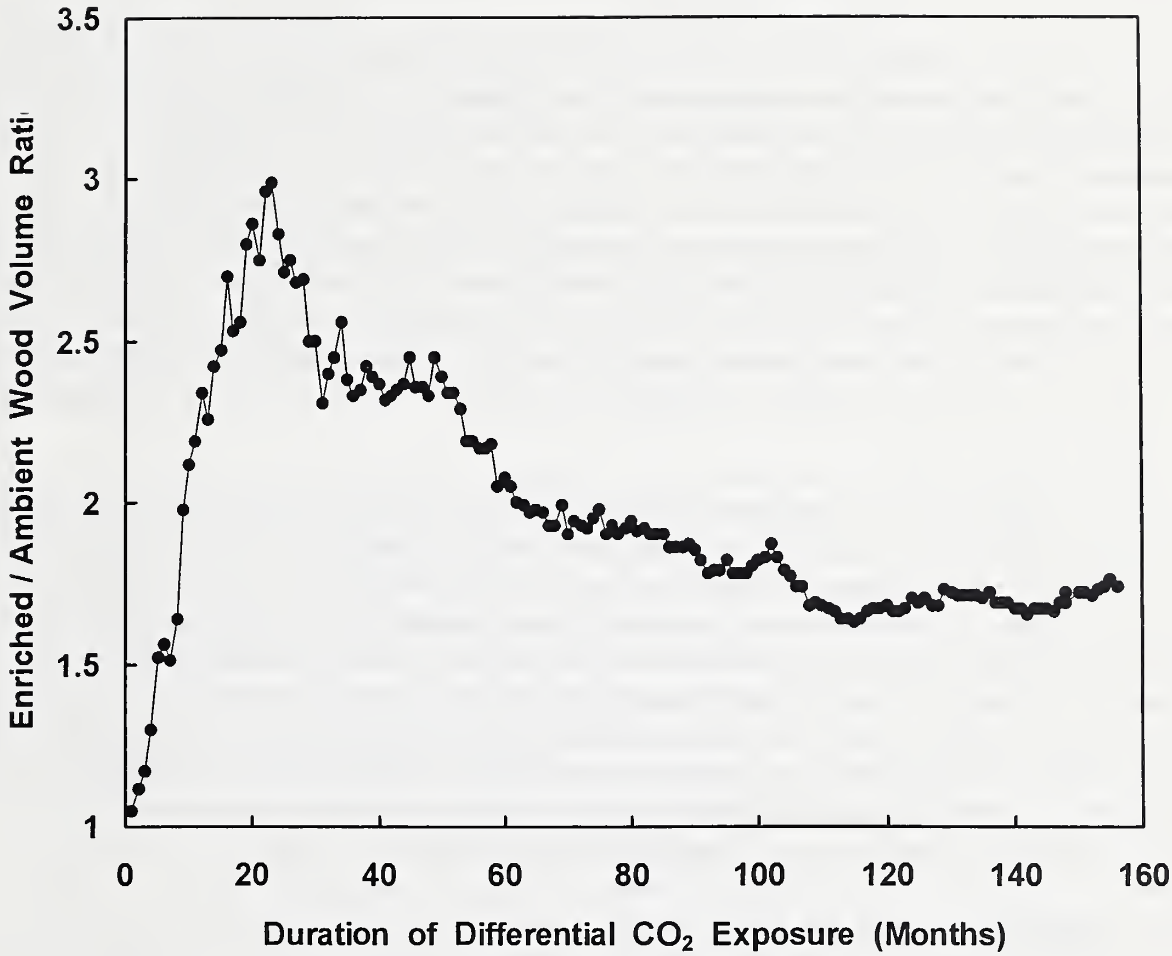


Figure 1. Ratio of volume of sour orange tree wood in CO_2-enriched chambers (700 μmol mol^{-1}) to that in ambient chambers (400 μmol mol^{-1}) versus duration of exposure to elevated CO_2.

Some newer studies are beginning to address these deficiencies. The free-air CO_2 enrichment (FACE) experiment at Duke University, for example, as well as a similar study at Oak Ridge National Laboratory, are being conducted on trees growing in their natural habitat. However, in both of these experiments the trees were already at least a decade old before the CO_2 treatments were established. FACE experiments on aspen and on poplar have begun in Wisconsin and Italy, respectively, on plantation saplings, but it will be several years before results are available. Open-top chamber experiments have also been initiated on scrub oak in Florida and on longleaf pine in Alabama. However, these studies are generally only projected to last about ten years. Although much important information will unquestionably be obtained from these experiments, what is learned may not be representative of the long-term equilibrium responses of the trees.

To illustrate this latter point, we present a 13-year history of the relative above-ground (trunk + branch) wood volume of our sour orange trees (Figure 1). These data were obtained from a relationship between trunk circumference and trunk and branch volume that we determined specifically for our trees at the ends of the second and third years of the experiment (Idso and Kimball, 1992). As can be seen from the results, the CO_2-enriched trees experienced a large initial CO_2-induced growth enhancement that increased their wood volume relative to that of the ambient-treatment trees by a factor of 3.0 at the 23-month point of the experiment. Thereafter, this ratio declined, rapidly at first – as has been observed in other studies (Idso, 1999) – but then more slowly. At the end of nine full years, however, the enriched/ambient wood volume ratio leveled off; and for the past 50 months, it has remained essentially constant at a mean value of 1.69 (which has also been the ratio for fruit yield).

Clearly, an experiment of only ten years' duration could well miss the important fact that the relative growth advantage enjoyed by CO_2-enriched trees early in their history may not be totally lost over the long haul, as some have supposed, but may continue indefinitely at a very significant, albeit reduced, level. In addition, it is unclear what different results might have been obtained if our sour orange trees had not been very small (30 cm tall) and very young (on the order of six months old) when the experiment was begun. This point, too, is extremely important; for the effects of atmospheric CO_2 enrichment very early in a plant's life cycle may be of great importance to how it responds to continued CO_2 enrichment later in life (Van Der Kooij et al., 1996; Jitla et al., 1997; Miller et al., 1997; Farage et al., 1998). Hence, experiments begun at the ten-year point of a tree's existence may also fail to reveal its true equilibrium response.

2. Synthesis and Integration:

That elevated CO_2 affects plant growth has been known for more than two centuries. Starting at about the beginning of the last century, specific studies to exploit the greater growth at higher CO_2, and thereby obtain higher agricultural yields, were conducted. Although impractical for open-field agriculture, CO_2 enrichment became a standard recommended horticultural practice in greenhouses during the 1960's wherever the greenhouses were closed and unventilated. In the late 1970s there was increasing concern about the rapid increase in atmospheric levels of CO_2 and what that might do to open-field agriculture and to natural ecosystems. This concern motivated Kimball (1983a) to review the prior work in this area, and he assembled some 430 of the early observations. He analyzed these data and concluded, i.e., synthesized, that a doubling of atmospheric CO_2 concentration would increase yields about 30%, on average, if global warming was minimal. Several similar synthesis papers have been written since, which include more recent literature and/or which examine particular classes of plants and/or particular plant processes or responses (Kimball, 1983b, 1986, 1993; Cure, 1985; Cure and Acock, 1986; Kimball and Idso, 1983; Poorter, 1993; Idso and Idso, 1994; Ceulemans and Mousseau, 1994; Morison, 1995; Wullschleger et al., 1997; Cotrufo et al., 1998; Curtis and Wang, 1998; Wand et al., 1999; Norby et al., 1999; Nakagawa and Horie, 2000; Reddy and Hodges, 2000).

Since the 1960s when computers first became widely available, plant scientists have developed models to simulate plant growth and yield. Because experiments cannot be conducted on every soil type and in every local climate, these models are an extremely valuable tool for encoding knowledge gained in relatively few experiments conducted under particular conditions and then providing the means to predict what will happen in other locations. They are especially useful for forecasting what may happen over wide regions under various scenarios of global change. Therefore, several such integrative studies have been done to predict the likely effects of global change on the agricultural productivity of various regions of the U.S. and of the world, as tabulated by the recent third assessment of the IPCC (2001). However, as discussed under the "Need for Research," we are concerned that the relatively simple models that have been used in such integrative studies are not able to simulate some plant responses to elevated CO_2, which may be important in determining overall crop responses.

In the past, we have developed models for guayule growth (Kimball, 1981), for energy relations of greenhouse crops (Kimball, 1986b), and for cotton growth (Wall et al., 1994; COTCO2 Model). In all three cases, after initial progress, work stopped in order to devote more time to experiments on effects of elevated CO_2 on plant growth. With the onset of the FACE wheat experiments in 1992-3, we became active in the GCTE (Global Change Terrestrial Ecosystems, a division of the IGBP or International Geosphere-Biosphere Programme) Wheat Network, a world-wide group of wheat modelers and experimentalists who are developing the capability to predict likely effects of global change on future wheat productivity. We contributed our data from two FACE x water and two FACE x N experiments to the effort. These data were desired by the group because they were needed for validating CO_2 response aspects, because they were of high quality and obtained at frequent intervals, and because there were many ancillary data. To date, at least ten modeling papers have utilized our FACE wheat data for validation (Grant et al., 1995a,b, 1999, 2001; Grossman et al., 1995, 1999; Kartschall et al., 1995; Barnes et al., 1997; Tubiello et al., 1999: Jamieson et al., 2001). For the first 5 months of 2000, we supported a Ph.D. graduate student, Mr. Talbot Brooks, to work with Dr. Robert Grant, author of the *ecosys model*, at the University of Alberta, in developing a C4 photosynthesis sub-model suitable for simulating the effects of elevated CO_2 and other environmental variables on sorghum photosynthesis. Thus, we have been at the periphery of plant growth modeling for some time.

In the aforementioned CRIS search, projects on modeling effects of global change appeared from the ARS Ft. Collins and Beltsville locations. The RZWQM root zone water quality model from Ft. Collins is a promising farm management tool, but questionable for the detailed physiological questions addressed herein. At Beltsville, the GLYCIM soybean model and the CPM cotton model appear to have the necessary physiological process detail, but they were written largely by Basil Acock who has recently retired, and we understand the group is being reorganized, so the opportunities for collaboration appear to be in limbo.

3. Alfalfa FACE Project:

Starting in 1983, researchers from the U.S. Water Conservation Laboratory (USWCL) and the adjacent Western Cotton Research Laboratory (WCRL) studied the effects of increased CO_2 at ample and limiting levels of water and nitrogen on cotton using open-top chambers (e.g., Kimball et. al., 1992; Kimball and Mauney, 1993). Recognizing limitations of the open-top chamber approach, the USWCL and WCRL scientists participated with other researchers, especially some from Brookhaven National Laboratory (BNL), in the design and implementation of a free-air CO_2 enrichment (FACE) project to conduct open-field CO_2 enrichment experiments. The first successful biological experiment was conducted in 1989 (Hendrey, 1993), followed by more cotton experiments in 1990 and 1991 with an additional water stress treatment. The results of these experiments are reported in 21 papers in a special issue of *Agricultural and Forest Meteorology* (Dugas and Pinter, 1994). In 1992 the FACE effort shifted from cotton to wheat, and two FACE experiments incorporating ample and limiting supplies of water were conducted from 1992-1994 and two more with ample and limiting supplies of soil nitrogen from 1995-1997. About 100 scientists from 43 different research organizations in eight countries participated in the cotton and wheat experiments (Wall and Kimball, 1993; Pinter et al., 1996). About 54 papers have resulted from the wheat experiments (see Curriculum Vitae for Kimball, Wall, and Pinter for lists), and several more are in preparation. Next the focus shifted to sorghum, a C4 crop, and two FACE experiments at ample and limiting water were conducted in1998 and 1999. Three papers (Rillig et al., 2001; Ottman et al., 2001; Cousins et al., 2001) have been accepted for publication from the sorghum experiments, and several more are in preparation or submitted.

A few experiments have been done to determine the response of alfalfa to elevated CO_2, but their results have not been very consistent. Daley et al. (1988) grew alfalfa in open-top chambers at CO_2 concentrations of ambient +0, +75, +150, and +300 μmol mol^{-1}, and they found that photosynthesis of young leaves was stimulated +40% by the +150 treatment. However, significant enhancement of yield, i.e. above-ground biomass, only occurred in 3 of 9 harvests, suggesting that much of the enhanced photosynthate was going to the large root system. In a similar study, Bunce (1993, 1995) grew alfalfa in CO_2-enriched open-top chambers, which had about as many weeds as alfalfa plants. The alfalfa biomass was altered +302, -31, and +47% and the combined alfalfa plus weed biomass was altered +56, -9, and +38% by enrichment to 700 μmol mol-1 over each of three years of the experiment, respectively. In the Swiss FACE experiment, in which the main species are ryegrass and white clover, Lücher et al. (2000) grew alfalfa in sub-plots within the FACE rings. The alfalfa had been inoculated with effective or ineffective nodulating strains of *Rhizobium*. They observed increases in growth of about +49% for the alfalfa with the effective strain of *Rhizobium* and elevated CO_2 at 600 μmol mol-1. On the other hand, the alfalfa with the ineffective strain averaged only about a 12% growth increase when ample N fertilizer was applied, and surprisingly decreased about 25% in growth with elevated CO_2 and low levels of N. We should also note that white clover (*Trifolium repens*), which is also a legume, increased above-ground growth by about 25% averaged over several years due to the elevated CO_2 (Hebeisen et al., 1997), but similar to Bunce (1993, 1995), they also found large year-to-year variation in the CO_2 response. Sgherri et al. (1998, 2000) recently described

another CO_2-enriched open-top chamber experiment on alfalfa that was also subjected to a short (5 day) drought. They examined several biochemical compounds related to photosynthesis and oxidative stress, but apparently have not yet reported on any agronomic aspects. We conclude from these works that there can be substantial variability in the response of alfalfa to elevated CO_2, and it is likely that, besides the effectiveness of the symbiotic *Rhizobium*, the partitioning between above- and below-ground organs may be very important. Above-ground agricultural yield may be enhanced at the expense of the below-ground root system with carbon-sequestration potential or vice versa.

For the reasons presented under the "Expected Significance" section, alfalfa is a crop whose response to CO_2 deserves more study especially in view of its potential for carbon sequestration and N_2-fixation. Following our demonstration that the FACE approach is the method of choice for conducting such research, about 28 FACE projects are now in operation or planned for various ecosystems around the world (http://cdiac.esd.ornl.gov/programs/FACE/whereisface.html). However, except for the small ancillary experiment in the Swiss FACE Project (Lücher et al., 2000), none has yet studied alfalfa; therefore, we are proposing to study it as the next logical continuation of the Maricopa FACE Project. However, it is contingent upon obtaining additional outside funding, and a proposal to obtain such funding is pending with NASA.

4. Piñon-juniper Rangeland CESAR-FACE Project:

As discussed in the "Need for Research," the piñon-juniper (PJ) ecosystem covers extensive mid-elevation areas in the Western U.S., and, because of its importance, additional research should be done to ascertain its response to elevated CO_2 and other interacting environmental variables. Free-air CO_2 enrichment (FACE) is the logical approach. However, unlike prior agricultural crop experiments at Maricopa AZ, the PJ ecosystem will have to be studied the year around; and because it is more heterogenous with larger vegetation, we will have to use larger diameter FACE rings. Therefore, the annual CO_2 requirement for conducting the research will be substantially larger than at Maricopa. If the price for CO_2 were the same as at Maricopa, the expense could be extremely prohibitive. Fortunately, however, an enormous geologic pool of CO_2 has been discovered within the PJ ecosystem near Springerville AZ, which is east-northeast of Phoenix near the New Mexico border, and the companies developing the CO_2 well field have offered CO_2 for a FACE project at a small fraction of the price paid in the prior Maricopa experiments. Moreover, the gas is quite pure with no toxins, and it is at favorable pressures for easy incorporation into a plastic pipe FACE distribution system. The presence of this CO_2 source greatly increases the feasibility for conducting such a piñon-juniper rangeland FACE project.

Led by Dr. George Koch from Northern Arizona University, Flagstaff AZ, a consortium of institutions and private companies has proposed to create a Science and Technology Center near Springerville AZ, for the study of Carbon Exchange and Sequestration in Arid Regions (CESAR). Besides utilizing the cheap CO_2 for FACE experiments, the Center would also feature flux towers to measure the present-day carbon, water, and energy fluxes, and it would also have a strong training and education component. Consortium members would include Northern Arizona University, Arizona State University, The University of Arizona, Ridgeway Industries (the company with the CO_2 development rights), Tucson Electric Power (an electric power company whose holdings within the

well field include excess buildings and land they are willing to donate to the project), as well as ARS scientists from the U.S. Water Conservation Laboratory and several rangeland research groups. Additional scientists from other institutions around the world are likely to become involved as well.

The CESAR Project is not yet fully organized, but outside funding is being sought. If it becomes a reality, we USWCL scientists would expect to contribute our expertise about operation of FACE experiments. We likely would also participate in the measurement of water and energy relations and in the development of techniques for remote sensing of the CO_2 and other treatment effects.

If the CESAR Project gets underway on rangeland, then at some point in the future it likely would become advantageous to move the agricultural crop FACE operations from Maricopa to Springerville. The much lower CO_2 cost would enable agricultural crops to be studied at much higher CO_2 concentrations than have heretofore been possible.

APPROACH AND RESEARCH PROCEDURES

Objective 1 - Sour Orange Trees

Experimental Design

To date, this experiment is the longest of its type ever conducted, and therefore, it has become extremely valuable. It began in July of 1987 by planting eight sour orange tree (*Citrus aurantium*, L.) seedlings directly into the ground at Phoenix AZ and enclosing pairs in four clear-plastic-wall open-top chambers. The trees have been maintained under optimum conditions of water and nutrient supply; and since mid-November 1987, half have been continuously exposed to ambient air of approximately 400 ppm CO_2 and the other half to air enriched with an additional 300 ppm CO_2 to a concentration of approximately 700 ppm. Details of the study are given in Idso and Kimball (1997), where we present results obtained over the first eight years of the experiment.

We are now in the 14th year of the study, and we estimate we will need to monitor the growth of the trees for about five more years in order to convincingly demonstrate that, after a large initial growth stimulation followed by a slow decline, the growth response to elevated CO_2 of the trees levels out at a constant value (Figure 1), i.e., we need to show that this value is maintained for a sufficiently long time that it we are confident it will be maintained over the remainder of the trees' life span.

While obtaining these important long-term growth data, as described by Idso and Kimball (1993, 1997), we also continue to observe yearly fruit production (numbers and fresh and dry weights) and fruit vitamin C and folic acid concentrations (via yearly determinations made by collaborators - Drs. Kevin Goodner and Wilbur Widmer - who are expert in these techniques). We also make near-weekly determinations of new branch lengths and fresh and dry weights, as described by Idso et al. (2000), new leaf numbers, areas and fresh and dry weights, as well as leaf fall-rates and leaf starch and chlorophyll concentrations, as described by Idso et al. (1993, 1996). In conjunction with other collaborators, we have additionally embarked upon some exploratory programs to determine

what we can learn about CO_2 effects on tree water use efficiency (via carbon isotope analyses of cores removed from the trees' trunks, in which Dr. Steve Leavitt is expert) and wood density (via x-ray densitometry analyses of the same cores, in which Dr. James Burns is expert). Likewise, we have launched an exploratory study into what we can learn about the effects of atmospheric CO_2 enrichment on the production of the glycoprotein glomalin, which is produced by fungi that live in symbiotic association with the orange tree roots, as well as the impact of CO_2-induced variations in this substance on soil aggregation, via techniques in which our collaborator, Dr. Matthias Rillig, is expert (Rillig et al., 1999).

Eventually, at the end of the experiment, we plan to conduct a detailed above- and below-ground biomass inventory of the leaves, branches of various size classes, trunks, and roots of various size classes and depths. Concentrations of C and N in the tree organs will be determined as well as those of the soil beneath the trees, radiating outward from the trees in concentric circles and downward to the bottom of the root zone. We will also enlist the help of our collaborators in studying the glomalin distribution in the soil at that time, as well as the distributions of other organic compounds that might be present; and we will investigate mycorrhizal characteristics and components of the soil food-webs we encounter beneath the trees.

For the sour orange tree experiment, Idso is responsible for the biological measurements, and Kimball is responsible for maintaining the CO_2 treatments.

Contingencies

We have already had much experience in all aspects of the studies we are currently conducting on the sour orange trees, and we feel confident we shall be able to successfully achieve the several goals.

Collaborations

Achievement of our primary objective – determining the long-term effect of atmospheric CO_2 enrichment on the growth and fruit production – can be done without outside collaboration. All of our collaborations deal with ancillary goals, such as medicinal attributes (Idso et al., 2000b) and vitamin C (Idso et al., 2001). Others in the data analysis stage include bulk wood density and water use efficiency from carbon isotopic analyses, as well as glomalin production from arbuscular mycorrhizal fungi.

Necessary (w/i ARS): Dr. Kevin Goodner, Citrus & Subtropical Products Lab., Winter Haven FL
Necessary (external to ARS): Drs. Steven Leavitt and Jim Burns, University of Arizona; Dr. Matthias Rillig, University of Montana;

Objective 2 - Synthesis and Integration

Experimental Design

One approach will be to assemble and analyze data reported in the literature from experiments around the world on the effects of elevated CO_2 and other interacting variables on plants, similar to past efforts by Kimball and by Idso (e.g., Kimball 1983a,b, 1985, 1986a, 1993; Kimball and Idso, 1983; Enoch and Kimball, 1986; Idso et al., 1997, 1988a,b; Idso, 1988, 1989, 1990, 1991a,b, 1992, 1993, 1995, 1997, 1999, 2000a,b; Rosenberg et al., 1990; Kimball et al., 1990, 1993a,b, 1997; Idso and Kimball, 1993; Idso and Idso, 1994). Generally, we plan to extract response values from the literature, organize them into logical subgroups, and then calculate means and confidence intervals (usually with necessary log transformations of ratio-type data, e.g. Kimball, 1983a)

An initial project will be to extract published data from free-air CO_2 enrichment (FACE) experiments conducted over the last decade. Several topics will be examined, including the effects of elevated CO_2 on: photosynthesis, stomatal conductance, canopy temperature, water use, plant water potential, leaf area index, shoot and root biomass accumulation, agricultural yield, radiation use efficiency, specific leaf area, tissue nitrogen concentration, nitrogen yield, tissue carbohydrate and other carbon-based compound concentrations, phenology, soil microbiology, soil respiration, trace gas emission/consumption, and soil carbon sequestration. Data will also be aggregated from species within functional groups (e.g., grape and cotton are both woody perennials and therefore might be expected to have similar responses, and if they do, then it is likely other woody perennials would behave similarly). Differences in responses of the various crops and functional groups will also be examined with regard to other interacting variables such as water supply, soil nutrient levels, temperature, etc. Comparisons will also be made between responses observed in the FACE experiments and those reported in prior reviews of chamber-based experiments.

A second synthesis and integration project will be a review of global warming and atmospheric CO_2 enrichment effects on carbon sequestration in soils and vegetation. This subject currently has worldwide attention. The recent (sixth) Conference of Parties (COP) of the Framework Convention on Climate Change (FCCC) meeting in The Hague deadlocked on this issue. Until the diverse array of scientific findings related to this topic can be harmonized within a robust conceptual framework in which all parties can have confidence, progress in developing rational domestic and international energy policies will be severely limited. In reviewing this subject, we will deal with both agricultural lands and natural ecosystems, such as grasslands and forests. We will look at both biomass production and decomposition, evaluating how these processes are affected by increasing temperature and atmospheric CO_2 concentration, singly and in combination; and we will determine how potential global change-induced alterations in these processes might increase or decrease terrestrial carbon storage in agricultural and natural settings. We anticipate this literature review will also tell us something about the current 'missing carbon' sink.

Many of the simple plant growth models use the concept of "radiation use efficiency" to calculate carbon fixed per unit of photosynthetically active radiation absorbed by the green vegetation. To

simulate growth under elevated CO_2 , the modelers simply use a larger value for this efficiency, but each one appears to be getting his/her values from particular experiments. Therefore, we plan to conduct a systematic review of the literature on the topic and then to synthesize a more general relationship between radiation use efficiency and atmospheric CO_2 concentration.

Another approach will be to utilize plant growth models, particularly *ecosys,* to assess the likely impacts of global change on the productivity and water requirements of agricultural crops, starting with wheat and sorghum. In nonspecies-specific *ecosys*, all simulation are performed at the plant/soil biochemistry scale, and integrated to provide organ, organism, soil layer, and landscape scale output. Specifically, *ecosys* uses components of the Farquhar model for determination of C3 and C4 photosynthesis, numerical solutions for soil chemistry (including N and C cyling) and energy balances, and explicit C allocation routines for growth and development, as well as sequestration. The *ecosys* model has been well validated for wheat (Grant et al., 1995a,b, 1999b, 2001b), and we expect it soon will be also for sorghum. It has also been validated with respect to several non-agricultural species, such as aspen, black spruce, and moss (Grant et al., 1999a; 2001a). Thus, using various scenarios of rising CO_2 and changing climate and scaling methodologies employed by the IPCC (2001), we propose to obtain more robust estimates of the impacts of global change on agricultural crops than obtained previously with simple models, such as cited in the third assessment by the IPCC (2001). The results will also be compared to those obtained previously with the simple models.

We also propose to conduct such impact studies for cotton with a sophisticated hourly-time-step model, but more work will have to be done with regard to model selection and development. No requisite species characteristic files have been written for *ecosys* nor has any validation work been done with it for cotton. Similarly, Wall et al. (1994) developed an initial working version of COTCO2 specifically to simulate the effects of elevated CO_2 and other climate variables on cotton, but it too has not been validated. It is also our understanding that a “cotton production model” (CPM) has recently been completed by the ARS Remote Sensing and Modeling Laboratory, Beltsville MD (V.R. Reddy, personal communication), which also has an hourly time step. However, its author has retired and it too has not been validated. Therefore, it is anticipated more model development work will have to be done for at least one of the cotton models before assessments can be made. However, such will not be undertaken until the wheat and sorghum works are completed, and by that time the situation with cotton may have changed.

Kimball, Idso, Wall, and Pinter are all responsible for synthesis work, and Kimball and Wall will do the modeling work.

Contingencies

If funding is obtained for Objectives 3 and/or 4, the Synthesis and Integration work will lower in priority but not be abandoned. This strategy is justified because we are in a unique position to pursue Objectives 3 and 4. We have teams of interested multidisciplinary collaborators capable of collecting near comprehensive sets of data, and we have the expertise to do the free-air CO2 enrichment. Thus,

we should try to achieve these objectives before team members become too engaged in other projects and disperse.

Collaborations

Necessary (outside ARS): Dr. Robert Grant, Univ. of Alberta; Mr. Talbot Brooks, Ariz. State Univ.

Objective 3 - Afalfa FACE Project (Contingent on obtaining outside funding)

Experimental Design

We propose to conduct a FACE experiment on alfalfa (*Medicago sativa* L.) at ample and limiting supplies of water for at least 3 years using a similar experimental design as that described previously with cotton, wheat, and sorghum (Figure 2; Wall and Kimball, 1993; Hunsaker et al., 1996; Kimball et al., 1999; Ottman et al., 2001).

A general objective is to determine the interacting effects of elevated CO_2 (FACE), soil water supply, and temperature on an alfalfa (Medicago sativa L.) ecosystem. Specific objectives and hypotheses are as follows:

1. Determine effects of elevated CO_2, water supply, and temperature on biomass (net primary productivity) and leaf area production, forage yield, and plant phenological development.

   Hypothesis 1a. There will be a significant growth response (~30%) at 200 μmol/mol of CO_2 above ambient under well-watered (Wet) conditions.

   Hypothesis 1b. There will be a somewhat larger growth response to 200 μmol/mol of CO_2 above ambient under the water-stress (Dry) treatment.

   Hypothesis 1c. There will be a larger relative response to elevated CO_2 under hot summer conditions than under cool winter temperatures.

   Hypothesis 1d. Phenology will not be significantly affected by elevated CO_2.

   Hypothesis 1e. Elevated CO_2 will have a positive effect on stand persistence.

2. Determine effects on sequestration of carbon in soil organic matter, soil CO_2 concentration, and soil respiration.

   Hypothesis 2a. There will be a significant increase in soil organic carbon due to elevated CO_2, especially at deeper depths.

Hypothesis 2b. There will be significant increases in the emissions of soil CO_2 in proportion to the biomass responses.

3. Determine effects on stomatal conductance, canopy temperature, energy fluxes, evapotranspiration, and soil water contents.

Hypothesis 3a. At times of minimal water stress, in the FACE plots there will be reduced stomatal conductances.

Hypothesis 3b. Elevated CO_2 will increase (make less negative) plant water potentials, more so under the water-stress than the well-watered treatment.

Hypothesis 3c. At times of minimal water stress, in the FACE plots there will be higher canopy temperatures (due to reduced stomatal conductances; accept 3a),

Hypothesis 3d. And higher sensible heat fluxes with reduced evapotranspiration.

Hypothesis 3e. And net radiation will be slightly reduced due to slightly more up-going long-wave radiation from warmer canopy temperature.

Hypothesis 3f. For a few days following irrigations, soil water contents in the rooted zone will be higher in the FACE plots for both Wet and Dry treatments.

Hypothesis 3g. Because of water conservation while soil water is not limiting, the soil water contents in the Wet plots at the end of each cutting cycle and growing season will be wetter under FACE,

Hypothesis 3h. And because of greater root ramification in the FACE-Dry plots, the soil water contents in the Dry plots will be drier under FACE.

4. Determine effects on photosynthetic biochemistry and net leaf and canopy photosynthesis.

Hypothesis 4a. Carbohydrates will accumulate in the FACE-grown alfalfa leaves and C3 pathway photosynthetic processes will be somewhat inhibited, particularly regeneration of RuBP,

Hypothesis 4b. But nitrogen will be non-limiting in legume alfalfa, so there will be a substantial increase in photosynthesis at elevated CO_2.

5. Determine effects on nitrogen fixation.

Hypothesis — There will be significant effects on the amounts of N_2 fixed that parallel the effects on biomass accumulation, as listed for Hypothesis 1.

6. Determine impacts on soil C and N mineralization and total microbial activity.

Hypothesis — Rates of mineralization and total microbial activity will be significantly increased by elevated CO_2.

7. Develop techniques for remote detection of net primary productivity of the alfalfa ecosystem subjected to varying levels of CO_2, water supply, and seasonal temperature.

Hypothesis 7a. — A functional relationship exists between the fraction of absorbed photosynthetically active radiation (fAPAR) captured by the plants for potential use in photosynthesis and multispectral vegetation indices (e.g. normalized difference vegetation index, NDVI) that can be used to predict potential carbon accumulation in the alfalfa ecosystem.

Hypothesis 7b. — The relationship developed in 6a will not be significantly affected directly by elevated CO_2, thereby implying that relationships between remotely detected signals and plant biophysical parameters will not change with time as the atmospheric CO_2 concentration increases in the future.

8. Determine impacts on herbivorous insects and consequent plant damage.

Hypothesis — There will be greater plant damage due to insect herbivory under elevated CO_2 while at the same time rates of insect development will be slowed.

Equally important objectives include assembling a database of the above measurements and developing and validating plant growth models (Holt et al., 1975; Denison and Loomis, 1989; Grant et al., 1995a,b) capable of predicting the effects of the increasing atmospheric CO_2 concentration and any concomitant climate change on the alfalfa ecosystem.

CO_2 treatment: A FACE apparatus will be used to enrich 25-m diameter circular plots by 200 μmol mol^{-1} CO_2 above ambient during the daylit period year-round (cutoff threshold will be an air temperature ≤ 5 °C) (Figure 2). Enrichment will occur from 50% emergence, through stand establishment, and for each successive cutting over the 3-year study. To account for any effect of the blowers, the Control rings at ambient CO_2 will have air flow like the FACE rings (Pinter et al., 2000). However, because we do not plan to operate at night, blower effects should be non-significant. We plan to stop enrichment at night because (1) studies on the effects of elevated CO_2 on dark

respiration have been inconclusive, (2) the blower effect on the microclimate at night (Pinter et al., 2000) introduces unnatural temperature and humidity effects which somewhat compromise direct use of the data for model validation, and (3) the savings in CO_2 costs can be better spent on additional measurement activities.

Irrigation treatment: We plan to impose our water supply treatments using a flood irrigation system, as done previously in our sorghum experiments (Ottman et al., 2001: Conley et al., 2001; Wall et al., 2001), by using a strip-split-plot design similar to that in Figure 2 with either side of each ring receiving a Wet or Dry treatment. Ideally, irrigations for the Wet (amply water supply) treatment would be initiated after 30% of the available water in the root zone is depleted, and they would be irrigated with an amount calculated to replace 100% of the potential evapotranspiration since the last irrigation (Fox et al., 1992). Practically, however, the irrigations and cuttings have to be coordinated in order to be able to operate machinery in the field without damaging the soil. Therefore, the Wet treatment will receive two or three irrigations per cutting, while the Dry treatment will receive one irrigation per cutting. The irrigations for the Wet treatment will be applied after the hay has been removed from the field and again at about half the interval of time to the next cutting. The irrigation for the Dry treatment will be applied after the hay has been removed from the field. In a study conducted in the San Joaquin Valley (Frate et al., 1988), irrigating once per cutting at the beginning of the growth cycle resulted in 87% of the yield of twice per cutting. Alfalfa is most susceptible to yield loss from water stress at the beginning of the regrowth cycle (Doorenbos and Pruitt, 1977; Brown and Tanner, 1983).

Adjustments will be made for any rainfall; but because the seasonal consumptive water use is typically over 2030 mm (Erie et al, 1982), while seasonal rainfall averages only about 150 mm, this adjustment is minor; and excellent control of the water supply is anticipated in this semi-arid desert region, as evidenced by the wide range in volumetric water content obtained in the prior FACE x water wheat and sorghum experiments (Hunsaker et al., 1996; Conley et al., 2001).

Crop culture: The alfalfa will be grown similar to commercial crops in the area using recommended agronomic practices. The cultivar CUF 101 was selected because it is a well-adapted to the low elevation deserts of Arizona and is the most widely grown cultivar in this area. It will be sown in October at a rate of 25 kg seed ha^{-1}. The seeds will be inoculated with an effective strain of *Rhizobium* bacteria. The soil will be sampled before sowing and analyzed for phosphorus concentration as a guide for pre-plant phosphorus fertilization. The soil will also be sampled in the fall of each year and analyzed for phosphorus as a guide for annual phosphorus fertilizer application in the winter. Phosphorus is the only plant nutrient that we expect to apply as fertilizer. Because alfalfa is a legume, we do not plan to fertilize with N, and indeed the effects of elevated CO_2 on N_2-fixation will be an important aspect of this experiment. Weeds will be controlled as needed following recommendations.

Biomass production and other agronomic measurements: Forage yield will be determined by cutting the main plots eight times per year at early flowering. More detailed measures of alfalfa growth will be recorded from sub-plots at each of the eight harvests and on weekly intervals for at least three

cutting cycles each year (spring, summer, and fall). These more detailed measures of plant growth include leaf biomass, stem biomass, plant height, and green leaf area index. Besides the main effects of elevated CO_2 on alfalfa growth at ample and limited water supply, after the 3 years of study over a wide range of summer to winter temperature extremes, the interactive effects between CO_2 and temperature will be examined, as will the effects of solar radiation. Because the annual pattern of solar radiation change leads that of temperature by a month or more, we anticipate being able to separate the effects of these two important environmental variables.

Soil carbon sequestration: Sequestration of carbon in the soil may be significantly increased by elevated CO_2, especially at deeper depths. We have gained experience examining soil organic carbon (SOC) change through repeated application of isotopic tracer techniques in FACE cotton (Leavitt et al., 1994), wheat CO_2xH2O (Leavitt et al., 1996), wheat CO_2xN (Leavitt et al., 2001), and sorghum (mss. in preparation). This method depends on the plant having or acquiring a carbon isotope composition that is sufficiently different from soil organic carbon that new carbon from the experiment entering the soil will alter SOC isotopic composition. The larger the difference in isotopic composition between SOC and inputs, the more sensitive the tool. In this study, we will dominantly employ a commercial CO_2 gas from geologic deposits which is most economical in our area. It has a $\delta^{13}C$= -5‰ for enriching FACE plots. By itself, it will result in FACE alfalfa plants with $\delta^{13}C$= -26‰, providing a tracer about 4.5 to 5‰ ^{13}C-depleted relative to SOC measured as -21 to -21.5‰ at the end of the previous sorghum experiments. In Control plots, the tracer will be a little stronger as the plants will have $\delta^{13}C$= -27‰, about 5.5 to 6‰ ^{13}C-depleted relative to the original SOC. Other studies have found this isotopic separation was sufficient to estimate carbon inputs. However, a stronger label would increase the power of this isotopic method to detect differences. Therefore, we plan to strengthen the isotopic tracer signal in the FACE plots by blending the main geologic CO_2 with at least 15% petroleum-derived CO_2 ($\delta^{13}C$= -40‰), which is somewhat more expensive. This will produce alfalfa plants of at least -27‰ if not even more ^{13}C-depleted. Extensive soil core samples will be taken before and after the experiment. Then, with estimates of new carbon from both FACE and Control plots, the difference will indicate net effect of CO_2 enrichment. Besides determination of new C from isotopes, we also will measure total C using standard chemical analyses, but this measure is less sensitive because of the large amount of C already present in soil. In addition, collection and $\delta^{13}C$ analysis of soil CO_2 at 2 depths will provide results for additional comparison between FACE and Control for belowground processes.

Photosynthesis and plant water relations: Leaf photosynthesis, conductance, and transpiration rates will be surveyed with a portable closed-exchange (transient) leaf gas (CO_2, H_2O) exchange system with a 250 cm^3 transparent cuvette (LI-COR, Inc., Model LI-6200, Lincoln, Nebraska, U.S.A.). Additional measurements of gas exchange rates will be made at solar noon (maximum photosynthetic rates) from the beginning of a soil dehydration cycle to just prior to rehydration (immediately following an irrigation until just prior to the subsequent one). We will monitor the leaf relative water content gravimetrically, and, with thermocouple psychrometers, we will measure total leaf water potential and its osmotic and turgor components.

Carbohydrate levels in the leaves of alfalfa vary with time during cutting cycles, and they are predicted by at least 3 alfalfa models (Holt et al., 1975; Denison and Looms, 1989; Grant et al., 1995a,b). We observed them to increase dramatically in leaves of wheat grown in elevated CO_2, particularly fructans (Nie et al., 1995b), and such accumulation has been shown to inhibit photosynthesis (Azcon-Bieto, 1983). Therefore, we will sample alfalfa leaves and stems, as well as roots whenever possible, when photosynthetic measurements are made. The samples will be flash frozen in liquid nitrogen and stored in a -80°C freezer. The samples will be freeze-dried, ground to pass a 20-mesh screen, and assayed for soluble sugars (sucrose, glucose fructose) and low and high molecular weight fructans and starch (Hendrix, 1992, 1993; Hendrix and Peelen, 1987). Key elements in the biochemical regulation of sucrose synthesis include bisphosphate (F2, 6bP) and sucrose phosphate synthase (SPS) (Stitt, 1991). For leaves stored at -80°C we will monitor levels for sucrose, FbP, F2-6bP, SPS, and cytosolic FbPase in conjunction with measurements of photosynthesis. Because carbohydrate accumulation in leaves will change with CO_2 and water-stress, these studies may also provide insight into how carbohydrates may serve as feed-back inhibitors of photosynthetic gene expression in the field, as proposed from laboratory studies (Krapp, 1991,1993; Sheen, 1990, 1992).

Biochemical assessment of the dark reactions of the photosynthetic apparatus will be performed concurrently with the survey of leaf photosynthesis and A/Ci curves. Leaves will be sampled, quick-frozen in liquid nitrogen, and stored at -80°C. These frozen leaf samples will be analyzed for soluble and total proteins, and enzyme assays will be conducted to evaluate Rubisco activities, activation states, and concentrations of active centers. Proteins will be extracted from an equal area of the frozen leaf samples. The extracted proteins will then be size-fractionated by polyacrylamide gel electrophoresis and either transferred to nitrocellulose membrane or stained with coomassie blue. The amount of protein in the individual lanes will be quantified by densitometric scanning of the stained protein bands. Rubisco, LHCII and the *a* and *b* subunits of the chloroplast ATPase are very abundant proteins and can be quantified easily with this procedure. We have antisera to Rubisco, PEPCase, and the b-subunit of the ATPase. We will use these to probe the proteins immobilized on the nitrocellulose filters, which will provide accurate identification and quantification of the proteins. Results from the western blots will help confirm those from the densitometric scans.

Biochemical assessment of light reactions of the photosynthetic apparatus, the quantum yield of PSII and any changes in photochemical and non-photochemical quenching will be monitored with a portable fluorometer (Model PAM-2000, Heinz Walz GmbH, Germany). Interpretation of fluorescence measurements will be used to determine how elevated CO_2 affects apparent electron transport and quantum yield in water-stressed compared with well-watered leaves. As was done in FACE wheat, thylakoid membranes will be isolated from the frozen leaf samples, with a modification of the protocol described by Nie et al. (1995a,b), to determine how additional thylakoid membrane proteins, particularly those associated with electron transfer complexes (PSI, PSII, cyt b6/f), are effected by elevated CO_2 and water stress. Thylakoid membrane proteins will be size fractionated by SDS-PAGE and either transferred to nitrocellulose membrane or stained with coomassie blue. Proteins will again be quantified by western blotting using antigens to key polypeptides of each complex. We have antisera to PSI and PSII reaction center proteins as well as cyt b6/f. We will use

these to probe the proteins immobilized on the nitrocellulose filters, which will provide accurate identification and quantitation of the proteins.

We propose to seek a molecular explanation for any observed *down-regulation* of photosynthetic proteins. We will examine the expression of genes encoding the proteins assayed above by the steady-state level of mRNA using northern blots. The leaves from each treatment will be wrapped in aluminum foil and immediately frozen in liquid nitrogen and stored in a -80 °C freezer. Total cellular RNA will be isolated from the frozen leaf samples using buffers containing guanidine hydrochloride followed by precipitation with lithium chloride (Hird et al., 1991). Equal quantities of glyoxal denatured RNA will be size fractionated by agarose gel electrophoresis and either stained or transferred to nylon membrane. The immobilized mRNA will then be probed with radiolabeled DNA fragments specific for a number of chloroplast and nuclear genes. In particular, we will look at steady-state levels of mRNA from *psaA/B*, *psbA*, *psbD*, *atpB*, *rbcL*, representative of chloroplast genes and nuclear from genes encoding LHCII, RbcS, FbPase, and SbPase.

From the perspective of the ecosystem, it is necessary to integrate individual leaf carbon exchange rates to the whole-plant, canopy and community levels. Therefore, eight steady-state whole-canopy gas exchange systems (Garcia et al. 1990; Brooks et al., 2001) will be used to monitor CO_2 and H_2O vapor exchange rates for all treatment combinations for two replications. All eight chambers will be run simultaneously and controlled from a central control trailer located on site. In addition, at bi-weekly intervals we intend to measure canopy carbon exchange rates across a broad range of atmospheric CO_2 concentrations (ambient to 1800 μmol mol^{-1}) and to monitor any changes in canopy architecture due to CO_2 or water level with a portable canopy analysis system (Model LI-6000, Li-COR, Lincoln, NE).

Energy and soil water balances and evapotranspiration: Canopy temperatures will be measured using carefully calibrated infrared thermometers that are switched between FACE and Control plots weekly (Kimball et al., 1994, 1995, 1999). Net radiation, soil heat flux, and sensible heat flux will be measured, and latent heat flux (i.e. evapotranspiration) will be determined using a residual energy balance approach (Kimball et al., 1994, 1995, 1999). Soil water contents will be measured using neutron scattering equipment and time domain reflectometry, similar to the methods used previously by Hunsaker et al. (1994, 1996, 2000) and Conley et al. (2001). Utilizing irrigation and rainfall amounts along with the soil water content data, a second estimate of evapotranspiration will be calculated as a residual in the soil water balance.

N_2 fixation: The fixing of inorganic atmospheric N_2 to organic forms of N is an important aspect of the alfalfa ecosystem. We will determine the overall effects of elevated CO_2 on nitrogen yield from measurements of biomass production, as described previously, and of the nitrogen concentrations of the tissues. In addition, we will determine the effects of elevated CO_2 on the symbiotic N_2 fixation in 2m x 2m sub-plots within the main plots. In half of each of these sub-plots, non-N-fixing plants will grown, but the entire sub-plot area will be fertilized with a small amount of fertilizer that has been highly enriched with ^{15}N. Following Lüscher et al.(2000), the percentage of N derived from symbiosis will be calculated from {%N = [1-(^{15}N atom excess $_{\text{fixing crop}}$)/(^{15}N atom percentage excess $_{\text{reference crop}}$)]

* 100} for both Control and CO_2 enriched plants (McAuliffe et al., 1958; Witty, 1983; Boller and Heichel, 1983). The reference non-N_2-fixing plants will be a near-isogenic non-fixing line of alfalfa germplasm (< 2% or less N_2-fixing activity; Barnes et al., 1990) and/or other non-fixing plants such as *Taraxacum officinale* L. (a species with deep tap root) or *Lolium perenne* L. (a species with shallow fine roots; Lüscher et al., 2000). A non-fixing alfalfa line would be preferred for the reference crop because then there would be more homogeneity in the crop canopy and few differences in rooting patterns and non-symbiotic N uptake. In addition, the number of nodules formed per plant will be determined by counting the number of nodules formed under both FACE and ambient CO_2 conditions. The effectiveness of the formed nodules and N_2 (C_2H_2) fixation activity of the nodules will be determined by the acetylene reduction technique (Havelka et al., 1982).

Soil N_2O and CO_2 emissions and soil CO_2 concentrations: We also propose to measure CO_2 and N_2O emissions throughout the growing season. Soil CO_2 will be collected at depths of 15, 30 and 50 cm in situ by means of permanently installed standpipes open at those depths. CO_2 from samples taken every 3 weeks will be cryogenically separated and isotopically analyzed. For surface soil efflux, PVC collars (ca. 20 cm diameter) will be partially pushed into the soil, and CO_2 flux will be measured using a LI-COR gas analyzer after placement of a cover over the open top of the collars. CO_2 samples will also be drawn into evacuated flasks, and they too will be cryogenically separated and analyzed isotopically. These collections and analyses should provide information about relative rates at which CO_2 is escaping from the soils of the FACE and Control plots, and the isotopic composition should reveal the relative contributions from different sources, especially in FACE plots where plant respired CO_2 should be very ^{13}C depleted relative to the SOC originally present in the soil.

Nitrous oxide emissions will be measured at about monthly intervals throughout the season within 1 m x 1 m soil subplots. Two subplots will be located in each FACE and Control ring for a total of 16 subplots. Measurements will also be made on a diurnal basis on selected days. Nitrous oxide flux will be measured using a non-steady-state (closed) chamber method (Matthias et al., 1980; Livingston and Hutchinson, 1995). We will analyze N_2O in air samples using a gas chromatograph equipped with an electron capture detector. Each chamber is made of opaque corrugated plastic and is temporarily deployed for 30 minutes on a 0.5 by 0.5 m base permanently inserted in the center of each soil subplot. Plastic syringes (50 mL) are used to sample air within each chamber at the time of deployment and 30 minutes later. Air samples are then immediately transferred from syringe to evacuated 10 mL Wheaton bottles for subsequent N_2O analysis in the laboratory. Gas samples from known standards are injected into evacuated Wheaton bottles in the field in order to assess potential losses of N_2O from the bottles during transport to Tucson. N_2O emission rate (g m^{-2} day^{-1}) is computed from the measured rate of increase of N_2O concentration in the chamber and the known height of the chamber. Chamber height is adjusted during the season in order to accommodate increased plant canopy height.

In addition to sampling N_2O emissions, denitrification rate will be evaluated using the acetylene inhibition method (Ryden et al., 1987; Terry et al., 1986) in undisturbed soil cores collected from each subplot. Simultaneously, microbial respiration will be evaluated as the amount of CO_2 evolved from soil in 1-L incubation jars using a CO_2 trap-titrimetric method (van Kessel et al., 1993). After

incubation and sampling, the soil cores (ca. 15 cm long by 5 cm diameter) will be dried to measure the water content, bulk density, and inorganic nitrogen (Keeney and Nelson, 1982). The N_2O flux and denitrification rate measurements should give important information about the relative loss of fertilizer N due to elevated CO_2 under water stress and well-watered conditions.

Remote sensing measurements: Measurements of solar reflectance and thermal emittance will be used to characterize dynamic agronomic and biophysical parameters of the alfalfa canopy on a continuous basis throughout the 3 year duration of the experiment. Data will be acquired several times a week at the whole canopy scale using ground based, wide band sensor systems having visible and near-infrared capabilities. Observations will be made at a time corresponding to a standardized solar zenith angle of 57° to minimize bi-directional reflectance factor complications that caused by widely varying illumination angles at different times of the year. Commonly used multispectral vegetation indices (VIs), such as the normalized difference vegetation index (NDVI), will be used to develop predictive relationships with percent cover, plant height, green leaf area index, and biomass of the alfalfa crop. These non-invasive, repeated measures of plant growth are expected to have less variation associated with them compared to traditional biomass samples. They will thus be of considerable value in differentiating treatment effects on regrowth of alfalfa after each harvest event. Multispectral VIs will also be used to estimate the fraction of absorbed photosynthetically active radiation (fAPAR) captured by the canopy for potential use in photosynthesis (Pinter, 1993; Pinter et al 1994). This is an important biophysical parameter required for determining the effect of elevated CO_2 on radiation use efficiency (RUE, the amount of biomass produced per unit of absorbed PAR). Temporal derivatives of VIs will also be examined for their utility in detecting alfalfa growth rates and in further quantifying differences between experimental CO_2 and irrigation treatments.

Fundamental questions regarding the direct effects of elevated CO_2 on spectral properties of alfalfa will be addressed using field portable spectroradiometers capable of measuring hyperspectral features (wavelength regions 3 to 10nm in width) in the visible, near-infrared, and short wave infrared portions of the spectrum. Canopy measurements will be taken at a standardized solar zenith angle of 57°. Single leaf data will be obtained using an external integrating sphere. Depending upon rates of plant growth and size of individual leaflets, these data will be acquired as often as weekly intervals during the height of the growing season. Data analysis will investigate treatment effects on narrow spectral features, spectral derivatives, overall spectral shape, and red edge position using traditional regression techniques.

The temporal course of plant water status between irrigations will be characterized non-destructively using several thermal indices that have been developed by USWCL scientists. Infrared thermometers will be used to obtain canopy surface temperatures from all replicates and treatment combinations about 1 hour after solar noon when plants are exposed to maximum atmospheric evaporative demand. The data will be used to compute the crop water stress index (CWSI) and estimate the ratio of actual to potential canopy evapotranspiration (Jackson et al., 1981; Idso et al., 1981). The water deficit index (WDI) which utilizes the thermal infrared plus an estimate of plant cover derived from VIs is expected to provide an accurate estimate of plant water status early in the regrowth period when plants are small and canopy cover is incomplete (Moran et al., 1994). These remote indices of plant

water status will be compared with less frequent measures of physiological water stress to provide a functional rationale for their use. Spatial variability within the FACE experimental field will be assessed periodically from a light aircraft or helicopter equipped with a thermal scanning radiometer.

Herbivorous insects: Elevated-CO_2-grown plants can affect the growth of herbivorous insects, as we have shown previously on cotton (Butler et al., 1985; Akey et al., 1988, 1989), and Awmack and Harrington (2000) have shown for alfalfa aphids on faba bean. However, alfalfa is especially noteworthy for attracting herbivorous insects, which attack during various times of the year and have different modes of feeding. Normally little active control is done, and at the time of cutting, the insects' food supply is removed and there is an abrupt change in microclimate (Pinter et al. 1975), which more or less resets the clock for the next cycle. We anticipate that this situation will provide opportunities for study of the effects of the elevated CO_2 and water stress treatments on these insects. Much of the work will be serendipitous, i.e., taking advantage of naturally occurring infestations. However, the initial infestations may be unevenly distributed, which would make interpretation of the data difficult. Therefore, we plan to augment the natural populations with infestations using insects in cages in some sub-plot areas. In particular, we will study the response of Lygus bugs, a serious pest complex on several crops in the U.S. and the world, and a foliage-feeding moth or leaf miner.

Plant growth modeling: We plan to utilize the data from the FACE alfalfa experiment to validate several aspects of *ecosys*, a mechanistic plant growth model with regard to several plant processes, namely the effects of CO_2, water supply, and seasonal weather on: biomass and leaf area production; sequestration of soil carbon; N_2-fixation, leaf photosynthesis, stomatal conductance, and plant water status; and canopy temperature, energy fluxes, and soil water content. Thus, the results from our specific experiments conducted at one place for a short time can be applied to future global change scenarios useful for exploring the policy implications of C sequestration and agricultural productivity in wider regions. At the same time, we expect that ecosys will provide a theoretical framework, which likely will help interpret the experimental data.

The names of the scientists on the FACE Alfalfa Project Team and their areas of responsibility for measurements are listed in the following table.

Investigator	**Measurement responsibiltiy**
Bruce A. Kimball	Overall management and energy and water balance measurements
Paul J. Pinter, Jr.	Remote sensing measurements
Gerard W. Wall	Plant water relations and photosynthesis measurements
Michael Ottman	Above-ground biomass production and other agronomic measurements
Steven W. Leavitt	Soil carbon sequestration and soil atmosphere measurements
Allan D. Matthias	Soil respiration and N_2O emissions measurements
Andrew N. Webber	Biochemical compounds involved with photosynthesis

George W. Koch	Mechanistic modeling of stomatal response to elevated CO_2
Dean Martens	N_2-fixation and other soil microbiological measurements
Bruce Hungate	Nitrogen cycling as related to elevated CO_2 and hydrology
Stephen Prior, Brett Runion & Allen Torbert	Carbon and nitrogen mineralization. And possibly root biomass.
David H. Akey and Jacquelyn L. Blackmer	Responses of herbivorous insects
Robert F. Grant & Talbot J. Brooks	Plant growth and soil process modeling

Contingencies

Conduction of the alfalfa FACE project is contingent upon obtaining additional outside funding. If funding cannot be obtained, we will do more of the Objective 2 synthesis and integration.

Collaborations

Necessary (within ARS); – Dr. Dean Martens, Soil Microbiologist, Tucson, AZ; Drs. David Akey and Jacquelyn Blackmer, Entomologists, Phoenix, AZ.; Drs. Stephen Prior and Allen Torbert, Auburn, AL and Allen Torbert, Temple, TX.

Necessary (external to ARS); – Dr. Michael Ottman, Department of Plant Sciences, University of Arizona; Dr. Steven Leavitt, Tree Ring Laboratory, University of Arizona; Dr. Robert Grant, University of Alberta; Mr. Talbot Brooks, Department of Geography, Arizona State University; Dr. Andrew Webber, Department of Plant Biology, Arizona State University; Drs. George Koch and Bruce Hungate, Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ.

Objective 4 - Piñon-juniper Rangeland FACE Project (Contingent on obtaining outside funding)

Experimental Design

Final details of the experimental design have not been decided, but a design under consideration is to build nine large (24-m diameter) FACE rings [using general methodology described in Hendrey (1993) and Miglietta et al. (1997)], with three rings at current ambient CO_2 concentration, three rings at 550 $\mu mol\ mol^{-1}$, and three rings at 750 $\mu mol\ mol^{-1}$. Because of the critical role of water in regulating ecosystem processes in the arid southwest, each ring (ambient, 550, and 750) will be split into two halves, one receiving 50% more than naturally occurring precipitation. Sub-plots will be clipped periodically at different frequencies to simulate varying grazing pressure.

Choosing an experimental design with adequate statistical power to discern ecologically important differences in the face of the heterogeneity of the piñon-juniper ecosystem is a concern. Rather than utilize a grid lay-out like we have in our Maricopa FACE field, it is likely that matched trio areas would be identified for each replicate block that wouldn't be a specified distance apart. The areas would be matched according to similar gross vegetation structure, slope, aspect, and soil properties. Probably a full growing season's worth of measurements will be done to establish a baseline condition for each plot before the CO_2 and other treatments are imposed.

The design with three CO_2 concentration levels, in contrast to most other elevated CO_2 experiments (and all FACE experiments), will allow us to test whether the effects of elevated CO_2 on C exchange and sequestration are linear over this range of CO_2 concentrations, spanning most of the projected increases in atmospheric CO_2 concentrations through the next century (IPCC, 2001). Some of the hypotheses to be tested and approaches used in these experiments include:

Hypothesis 1: Elevated CO_2 will increase rates of CO_2 uptake by ecosystems from the atmosphere, but (1) these increases will be larger in woody species (dominated by the more responsive "C3" photosynthetic pathway) than grasses (dominated by the less-responsive "C4" photosynthetic pathway) , and (2) partitioning of the extra C taken up in elevated CO_2 among ecosystem compartments varying in turnover time will strongly influence the way rates of C exchange translate to long-term C sequestration in wood and soils.

We will measure rates of net ecosystem C exchange in ambient and elevated CO_2 concentrations using open gas exchange systems (Garcia et al., 1990; Brooks et al., 2001). The geological source of CO_2 is 'dead', containing undetectable amounts of ^{14}C (this CO_2 differs only slightly from atmospheric CO_2 in stable C isotope [^{13}C] composition). We will use this depletion in ^{14}C to trace carbon flow to pools of varying turnover times, including soil fractions and wood. Collaborators and PIs include experts in radiocarbon tracing (Leavitt) and soil C analysis, including fungal pools. Measurements of natural abundance of ^{14}C will be made on the accelerator mass spectrometer in the Laboratory of Isotope Geochemistry at the University of Arizona. Because our design includes two levels of elevated CO_2, we will be able to quantitatively assess the effects of increased CO_2 (550 to 750 $\mu mol\ mol^{-1}$) on carbon partitioning and the implications for long-term C sequestration. Additionally, we will use ^{13}C labeling techniques to track rates of C uptake and incorporation into soil by different plant growth forms (see below).

Hypothesis 2: Elevated CO_2 will favor shrub encroachment into grasslands, and the increase in C uptake and sequestration caused by invading deep-rooted shrubs will be greater than the direct effect of elevated CO_2 on rates of C exchange and sequestration in the grassland ecosystems.

Sampling for biomass production of the grasses will be done, whereas the wood volume increase of the shrubs will be made from dimensional measurements and allometric relationships. Numbers of plants of each species will be tabulated. In addition, the dominant woodland (piñon, juniper, rabbitbrush) and grassland species differ in stable isotope composition from each other due to their different photosynthetic metabolisms, and the differences are reflected in the soils developed under

these different plant groups. This provides a powerful C isotope tracer which we will use to document the incorporation into grassland soil ($\delta^{13}C$ = - 15 ‰) of C from the deeply rooted shrubs ($\delta^{13}C$ = -23 to -27 ‰), and how this process is affected by elevated atmospheric CO_2.

Hypothesis 3: Elevated CO_2 will cause partial stomatal closure during times when there is sufficient moisture, which will decrease transpiration per unit of leaf area of both C3 shrubs and C4 grasses. Consequently, canopy temperatures ofboth shrubs and grasses will increase. Water use efficiency will increase under elevated CO_2 for both. However, there will be a CO_2 growth response of the C4 grasses only drier conditions, whereas the C3 shrubs will respond under moist conditions as well. An ancillary hypothesis is that the elevated CO_2 will enable the grasses to withstand greater grazing pressure only under the drier conditions.

Soil water content will be monitored by TDR or neutron scattering, and water use determined from changes using a soil water balance (e.g. Hunsaker, et al., 1996). Net radiation, canopy temperatures, air temperatures, and soil heat fluxes will be measured components ofthe energy balance, while water use will be determined as the residual (e.g. Kimball et al., 1999). Plant water potential will be determined occasionally using sampled leaves in pressure bombs and psychrometers (e.g. Wall et al., 2001).

Not all responsibilities have been defined for the Piñon-Juniper FACE Project Team, and several more members will be added in the future. However, it is likely the following scientists will have areas of responsibility as listed in the following table.

Investigator	**Measurement responsibility**
George W. Koch	Overall management and mechanistic modeling of stomatal response to elevated CO_2
Bruce A. Kimball	Initial establishment of FACE apparatus and energy and water balance measurements
Paul J. Pinter, Jr.	Remote sensing measurements
Gerard W. Wall	Plant water relations and photosynthesis measurements
Jack Morgan	Biomass productivity and photosynthesis
Steven W. Leavitt	Soil carbon sequestration and soil atmosphere measurements
Bruce Hungate	Nitrogen cycling as related to elevated CO_2 and hydrology
Robert F. Grant & Talbot J. Brooks	Plant growth and soil process modeling

Contingencies

Contingent upon obtaining outside funding. If such funding is not obtained, we will focus more on Objective 2 synthesis and integration.

Collaborations

Necessary (within ARS) – Dr. Jack Morgan, Ft. Collins, CO

Necessary (external to ARS) – Drs. George Koch (Leader of CESAR Project) and Bruce Hungate, Ecologists, Northern Arizona University, Flagstaff, AZ; Dr. Steven Leavitt, Tree Ring Laboratory, University; Dr. Robert Grant, Plant Growth Modeler, University of Alberta; Mr. Talbot Brooks, Modeler, Arizona State University.

PHYSICAL AND HUMAN RESOURCES

1. Sour orange trees: The physical and human resources available and necessary to accomplish our research objectives over the next three years are basically the same as they have been since the beginning of this very-long-term project. We have the needed equipment, and about 1.0 FTE of technician time will be directed to the project.

2. Synthesis and integration: We have the requisite PC computers and access to higher speed Unix computers at Arizona State University (ASU). We have a small library at the USWCL and access to the library at ASU. We also utilize the resources of the National Agricultural Library. Two FTE of technician time will be directed to the project. However, as mentioned at the outset, this activity will have lower priority than FACE experiments on alfalfa and/or piñon-juniper if they get funded. In the latter case, the two FTE of technician time would be mostly directed there.

3. Alfalfa FACE Project: The USWCL has the requisite FACE apparatus, as used in the 1998 and 1999 FACE sorghum expeiments, for maintaining controlled elevated CO_2 concentrations over open-field plots, although a CO_2 storage tank would need to be leased or purchased. The University of Maricopa, Maricopa Agricultural Center, has the land and necessary farming equipment. They also can supply irrigation water, and a Specific Cooperative Agreement or other arrangement would be made with them to conduct the experiment. The USWCL also has the necessary balances and drying ovens for biomass measurements; the data loggers and micro-meteorological instruments for energy balance measurements; the pressure bombs, leaf psychrometers, and other sensors for determining plant water status; and the infrared thermometers, black-body calibrator, hyperspectral radiometer, and other sensors for remote sensing aspects. Two FTE of permanent technician time would be directed to the project, but this will not be enough. Outside funding is being sought for more temporary technical assistance and also for an engineer to be responsible for installation and maintenance of the FACE and irrigation treatments. Our collaborative partners also require more technicians (or graduate students).

4. Piñon-juniper FACE Project: This will be a new project, so considerable equipment will have to be purchased and installed. Fortunately, Tucson Electric Power has a generating station with excess buildings and land within the CO_2-well field whose use they have offered to the project. Power, water, and communication connections can also be made at their facility, so it is likely that no installation of long cable or pipe lines will be needed. Nevertheless, in spite of the TEP infrastructure, FACE apparatus will have to be be built and installed.

If the Alfalfa FACE Project gets funded and is in operation at Maricopa, many USWCL instruments and the technicians listed above will not be available for the Piñon-Juniper FACE Project at Springerville. Therefore, additional instruments and technical help will have to be obtained. On the other hand, if the Alfalfa FACE Project does not get funded, the USWCL resources can be directed to Springerville.

MILESTONES AND EXPECTED OUTCOMES

	Research Objective or Area of Study			
Date	**1. Sour Orange Trees (Idso, Kimball)**	**2. Synthesis & Integration (Kimball, Idso, Wall, Pinter)**	**3. FACE Alfalfa Expt. (Kimball, Wall, Pinter)**	**4. FACE Piñon-Juniper Rangeland Expt. (Kimball, Wall, Pinter)**
Jan. 2001	Harvest fruit & tabulate monthly growth increments for 2000.	Review of free-air CO_2 enrichment (FACE) effects on agricultural crops completed.	Proposal submitted to NASA for funding.	Rough plan and pre-proposal completed.
Jan. 2002	Ditto for 2001 + folic acid production + soil fungal growth & glomalin & soil structure.	Above FACE review published, and review of carbon sequestration completed. Paper on elevated CO_2 effects on canopy temperature and crop production areas written.	If selected for NASA funding, will install FACE apparatus and plant alfalfa in fall 2001. If not, then timetable will pushed forward accordingly until funding finally achieved.	Second stage planning completed, and proposal prepared and submitted to funding agency.
Jan. 2003	Ditto for 2002 + wood density & strength + water use efficiency.	First regional study with *ecosys* on wheat completed. Paper written on relationship between radiatio use efficiency and CO_2 concentration.	Tabulation and review of first year's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data.	If selected for funding, initiate experiment in spring of 2002. If not, timetable will be delayed accordingly until funding finally achieved.
Jan. 2004	Ditto for 2003 + differing sunlit & shaded growth & fruit & antioxidant + history of leaf starch & sugar production + leaf senescence & fall history.	First regional study with *ecosys* on sorghum completed. Cotton model selected and regional study intiated.	Tabulation and review of second year's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data.	Tabulate and review of initial season's baseline measurements at ambient CO_2.
Mar. 2004	End of time for this proposed project plan.			
Jan. 2005	Ditto for 2004. This marks the minimum length of time to be sure that the CO_2-enriched trees have achieved a constant relative growth advantage over the ambient-treatment trees (Figure 1) that can reasonably be expected to continue throughout the remaining life of the trees.		Tabulation and review of third year's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data. Papers written on these topics.	FACE treatment starts spring of 2004. Tabulation and review of first season's growth, remote sensing, energy and water balance, photosynthesis and water relations, and other data.

LITERATURE CITED

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IRRIGATED CROP MANAGEMENT UTILIZING REMOTE SENSING

Paul J. Pinter, Jr., Research Biologist
Edward M. Barnes, Agricultural Engineer
Glenn J. Fitzgerald, Research Agronomist
Thomas R. Clarke, Physical Scientist
Douglas J. Hunsaker, Agricultural Engineer
Bruce A. Kimball, Supervisory Soil Scientist
Floyd J. Adamsen, Soil Scientist
Gerard W. Wall, Plant Physiologist

PROJECT SUMMARY

We propose to conduct agricultural water management research using remote sensing approaches with the following objectives: (1) Develop and critically assess methods for using reflected solar and emitted thermal energy to quantify temporal and spatial variations in crop response to water, nutrients, and pests. Special emphasis will be placed on developing algorithms that perform reliably regardless of plant phenology and biomass, and thus can be used for crop management purposes throughout the entire growing season. (2) Develop and improve irrigation scheduling methodologies that are responsive to actual crop evapotranspiration (ET) and irrigation requirements. Multispectral vegetation indices will be used to develop and test real time, basal crop evapotranspiration coefficients (K_{cb}) which are expected to provide significant improvements of actual crop ET prediction for use with irrigation scheduling procedures for cotton and wheat. (3) Develop methods for using remotely sensed observations in precision management of water, nutrients, and pests in irrigated crops. Remote data will be tested as a means to direct an efficient sampling routine. It will also be used in conjunction with simple and process-oriented crop growth and management models to provide spatial information needed to run the models with a minimum amount of input. Research accomplished during this project will result in improved methods for quantifying actual crop water and nutrient needs, as well as methods to detect water, nutrient, and pest related stresses. This will enable growers to make better informed, within-season management decisions about the need to irrigate, fertilize, or control pests on an "as needed" basis within their farms or fields and particularly in situations where variable rate technology is in use.

OBJECTIVES

1. Develop and critically assess methods for using reflected solar and emitted thermal energy to quantify temporal and spatial variations in crop response to water, nutrients, and pests.

   Spectral reflectance and thermal emittance properties of soils and plants will be used to detect environmental stresses that limit productivity of agricultural crops. Traditional vegetation indices such as the NDVI will be combined with other spectral information that is less sensitive to canopy biomass in order to reduce problems associated with partial canopy conditions and enable identification of water and nutrient related stresses throughout the entire growing season.

2. Develop and improve irrigation scheduling methodologies that are responsive to actual crop evapotranspiration and irrigation requirements.

   Basal crop coefficients (K_{cb}) will be derived from multispectral vegetation indices then refined to provide improved water management capabilities within the framework of accepted FAO-56 irrigation scheduling procedures. A two-dimensional Crop Water Stress Index (CWSI) which accounts for partial canopy conditions will be used to more accurately quantify real-time crop water use and map its spatial variability throughout the entire growing season.

3. Develop methods for using remotely sensed observations in precision management of water, nutrients, and pests in irrigated crops.

   Statistical and image analysis procedures will be used with multispectral reflectance and thermal emittance imagery of agricultural fields to guide efficient sampling ground procedures, define management zones, and generate maps of crop density and conditions related to water, nutrient, and pest stresses. Indices related to crop nutrient status, transpirational potential (*i.e.* K_{cb}), and water stress (CWSI) will be integrated into process-oriented crop models to predict spatial and temporal variability in plant response across a field and provide a framework for precision management of water and nutrients.

NEED FOR RESEARCH

Description of the Problem to be Solved

Industrialized nations are poised on the threshold of dramatic changes in the way natural resources are surveyed, monitored, and managed. Growers are being encouraged to increase their productivity per unit of land and water in order to feed a hungry world. Agricultural resource managers are recognizing within-field variability in potential productivity and seeking ways to customize their growing practices to exploit that variability (National Research Council, 1997). Environmental guidelines mandate more efficient and safer use of agricultural chemicals. As a result, today's farmers require an increasing amount of information on field and plant conditions to manage their crops in a sustainable and environmentally sensitive manner and still make a profit. Not only does this information need to be accurate and consistent, but it also needs to be available at temporal and spatial scales that match the farmer's capability to vary water and agrochemical inputs (*i.e.,* precision crop management).

A large body of research spanning the past three decades has demonstrated the potential for remote sensing (RS) to deliver this type of spatial and temporal information on soil and crop response to dynamic environmental conditions and management. Now, when combined with extraordinary advances in precise global positioning satellite (GPS) devices, microcomputers, geographic information systems (GIS), and enhanced crop simulation models, farmers can use remote sensing from ground, aircraft, and satellite platforms to monitor and manage their crops on a routine, cost-effective basis. The successful application of RS technology to agricultural resource management requires a basic understanding of how changes in plant growth, form, and function affect spectral reflectance and thermal emittance properties of crops in the field.

Beyond this fundamental requirement however, a number of significant problems still need to be overcome before RS will be able to deliver on promises made to consumers and agriculture towards the end of the last century. How, for example, can signals associated with plant water-, nutrient-, and pest stress conditions be discerned for certain when scenes are composed of varying amounts of plant and soil components? What is the best way for RS to provide additional spatial and temporal information needed to improve the performance of existing irrigation scheduling and crop growth simulation algorithms? These are research issues that are becoming more important as precision agriculture assumes a greater role in producing America's

food and fiber. They are also examples of the problems that we propose to explore in this project's research plan. One has only to look at the somewhat disappointing failure rate among of commercial remote sensing ventures to recognize that this is high risk research that is best addressed through a long-term national research program.

Relevance to ARS National Program Action Plan

This project relates broadly to several components within the National Program for Water Quality and Management by providing approaches for monitoring the response of soils and crops to management practices and environmental conditions, for detecting the occurrence of growth-limiting plant stresses, and for quantifying biophysical processes such as evapotranspiration (ET) and absorption of solar energy used in photosynthetic pathways.

Objective 1 relates to the Irrigation and Drainage Management Component, Problem Area (PA) 2.1, Economical Irrigated Crop Production, Goal 1 - Develop water, pest, and nutrient management practices and technologies that protect the environment and improve the economic benefits of irrigation and drainage. Objective 1 also has linkages with National Program (NP) 204 Global Climate Change, and NP 305 Crop Production.

Objective 2 relates to PA 2.3, Water Conservation Management, Goal 1 - Develop technologies to quantify and control a broad range of water supplies and uses, and Goal 2 - Develop cultural and management practices for agriculture, turf, and urban landscape plantings that maximize the return for irrigation water used.

Objective 3 relates to PA 2.2, Precision Irrigated Agriculture, Goal 1 - Develop precision agricultural irrigation systems that incorporate water management strategies and remote sensing technologies into site-specific management for the production of agronomic and high-value crops, and PA 2.3, Water Conservation Management, Goal 3 – Develop improved agricultural practices and systems that mitigate the adverse effects of irrigation on water quality and the environment. Objective 3 also has links to NP 207, Integrated Agricultural Systems.

Potential Benefits

Research conducted in this project will result in improved methods for quantifying crop water, nutrient, and pest related stresses and actual irrigation water requirements. This will enable growers to make better informed, within-season management decisions regarding irrigation timing and delivery volumes, fertilizer needs and pest control on an "as needed" basis within their farms or fields. Farmers will be able to initiate remedial actions that will maximize economic benefits and minimize detrimental environmental impacts. Incorporating RS soil and plant information into crop irrigation, growth simulation, and management models will provide spatial information that is needed to use these models on a finer spatial scale for describing within field variability and will increase their utility for precision agriculture approaches such as generating variable rate fertilizer application maps. In addition, the enhanced models will add predictive capabilities to somewhat less frequent remote observations, an important benefit in

regions where cloud cover interferes with regular satellite or aircraft coverage.

Anticipated Products

This project will result in new and improved RS approaches for identifying different types of plant stress and quantifying their intensity, regardless of plant biomass or phenological stage. Products for scheduling the timing and amounts of irrigation and fertilizer applications are also anticipated. Multispectral, real time crop coefficients for determining the seasonal course of actual crop ET will be developed for cotton, wheat, and alfalfa. The project will also lead to new methods for combining the spatial information from RS and the predictive capabilities of crop management models, and provide specific approaches for utilizing RS capabilities in the emerging field of precision agriculture.

Customers

Stakeholders who will benefit from the research include growers; crop, soil, and irrigation consultants; cooperative state extension personnel; commercial providers of RS products; and commercial entities and governmental agencies that control or regulate water supplies. Algorithms developed during the course of this research will have a direct bearing on yield prediction, and thus have potential use for agencies such as NASS or FAS who forecast yields over broad geographic regions. NASA and commercial RS providers will be active partners in developing practical farm management and regulatory applications of RS imagery.

SCIENTIFIC BACKGROUND

Objective 1 – Crop Response

The theoretical basis for using RS in agricultural resource monitoring has been established in numerous laboratory and field investigations over the past four decades (Monteith, 1959; Gates et al. 1965; Knipling, 1970; Gausman and Allen, 1973; Bauer, 1975; Jackson, 1982; Asrar et al. 1989). These studies have shown vegetation to be rich in spectral features that might be used for identification and stress assessment purposes (Gates et al., 1965; Gausman and Allen, 1973). Healthy, green vegetation has low reflectance and transmittance in the visible regions of the spectrum (400 to 700 nm) due to strong absorptance by plant pigments. However, a number of different types of stress often cause chlorophylls to decline, allowing expression of other pigments (*e.g.* carotenes and xanthophylls), broadening the green reflectance peak (~550 nm) towards the red, and producing a characteristic chlorotic appearance (Adams et al. 1999). In the near-infrared (NIR, 700 to 1300 nm), green leaves typically display high reflectance and transmittance, since there is very little absorptance by photosynthetic pigments and considerable scattering by mesophyll cells. When plants are stressed, NIR reflectance decreases, albeit proportionately less than the visible increases. The abrupt "red edge" transition normally seen between visible and NIR in vigorous vegetation shifts towards shorter wavelengths and then disappears entirely in senescent vegetation. Optical properties of leaves in a third region of the solar spectrum, the middle- or short wave-infrared (SWIR, 1300 to 2500 nm), are strongly

absorbed by water but reports in the literature suggest there is insufficient variation over biologically significant ranges of plant water content for the practical use of the SWIR as a diagnostic tool (Bowman, 1989). Energy in the thermal infrared (TIR) atmospheric "window" (~8 to 14 μm) has proven very useful in assessing water status. It is controlled primarily by latent and sensible energy fluxes at the surface of soils and plants and is somewhat decoupled from their optical properties (Jackson, 1982). Physical and biological stresses that interfere with transpiration result in elevated plant temperatures.

Compared with plants, spectral signatures of most agricultural soils are relatively simple. Nevertheless, the reflectance of soils contributes significantly to the total surface reflectance, especially early in the season when plants are small. Agricultural soils generally exhibit gradual increases in reflectance throughout the visible and NIR (Condit, 1971; Stoner and Baumgardner, 1981). High moisture and organic matter contents cause lower reflectances while smooth surfaced soils tend to be brighter. Occurrence of specific minerals in the soil have been associated with unique spectral features (*e.g.*, higher red reflectance in the presence of iron oxides). The SWIR spectra of soils display more structure than those observed in shorter wavelengths but seem dominated by moisture content and litter amounts.

From a RS perspective, crops represent a complex mixture of soil and vegetation components that vary dynamically over the season. It is readily observable that overall scene reflectance and emittance change markedly as the vegetation component increases from planting to harvest. Less obvious, but not less important, spectral properties of underlying soils vary with moisture content, tillage, and litter fall and decomposition. Spectra of plant components change with age of tissues, stage of growth, and architectural arrangement of organs. Apparent spectral properties are also strongly affected by illumination and viewing angles, row orientation, topography, meteorological phenomena, and other factors that are not directly related to the plants (Jackson et al., 1979; Pinter et al., 1983, 1985, 1987; Qi et al.,1995). The real challenge for agricultural RS is to be able to separate spectral signals originating with a plant response to a particular stress from normal plant biomass or the background "noise" that is introduced by exogenous non-plant factors.

Estimating Green Biomass, fAPAR, and K_{cb}: When the goal is simply to determine how much green plant material is present, vegetation indices (VIs) computed as differences, ratios, or linear combinations of reflected light in visible or NIR wavebands usually provide very good, season long performance (Tucker, 1979; Richardson and Wiegand, 1977; Jackson and Huete, 1991). The simple ratio (NIR/Red) and normalized difference vegetation index [NDVI=(NIR-Red)/(NIR+Red)] have gained wide acceptance for estimating plant cover, green plant biomass, and leaf area index. Soil adjusted VIs such as SAVI and modified SAVI have been developed that minimize variation in soil reflectance (Huete, 1988; Qi *et al.,* 1994). Of particular interest, VIs can also provide a remote estimate of the fractional amount of solar energy captured by the canopy for potential use in photosynthesis (fAPAR) for use in plant modeling studies (see scientific background in Objective 3) as well as a basal crop coefficient (K_{cb}) used in irrigation scheduling algorithms (Bausch and Neale, 1989; Choudhury et al., 1994; also refer to Objective 2 below).

Detecting Crop Stress: Wideband VIs are often used in a relative sense to provide maps of "crop vigor" for management purposes (Blackmer et al., 1996). For the most part, however, VIs lack diagnostic capability for determining why biomass is at a certain level or for identifying a particular type of stress. Inadequate nitrogen fertilizer, for example, can result in the same NDVI as that from a sparse canopy caused by low seeding rate or drought. To a certain extent, diagnostic ambiguity can be reduced by including reference strips that are known to have sufficient N supplies within the field (Blackmer et al., 1995). But in practice, such comparisons are expensive to implement and difficult to achieve without incurring a cumulative bias in the signal from the reference strip. A definitive solution that uses an absolute measure instead of a relative comparison is more desirable and practicable.

There are a number of different strategies for accomplishing this goal. One is to look for spectral features that are uniquely associated with a particular stress. Those that alter the ratio between chlorophyll and accessory pigments should be clearly detectable with high resolution spectroradiometry (*viz.* Maas and Dunlap, 1989; Buschman and Nagel, 1993). Many indices based on narrow band spectral features sensitive to pigment concentrations have been proposed to identify specific nutrient and water stresses (Gamon et al., 1990, 1992, 1997; Fernandez et al. 1994; Filella et al. 1995; Yoder et al., 1995; Gao, 1996; Peñuelas et al., 1997a, b, c; Peñuelas and Filella, 1998; Blackburn, 1998; Adams et al., 1999, 2000). Usually these techniques compare the reflectance or absorptance signal at a pigment-sensitive wavelength with that in a region that is less affected by the stress. Many of these indices are also correlated with green biomass and, thus, cannot be applied uniformly throughout the entire growing season. At present, quantitative research on plant stress effects on narrow band features is still in its early stages - detailed spectral signatures of major crops grown on different soils and exposed to various management regimes and environmental conditions have not been thoroughly investigated. It is, however, expected to lead towards new approaches for using spectral signatures to unambiguously identify different types of plant stress throughout the entire growing season. In fact, the SPAD meter (Minolta Corporation) and The Observer (Spectrum Technologies, Inc.) are commercial examples of handheld devices that are used to infer N concentration in single leaves or canopies based on the differential absorption of light in relatively narrow far red and NIR wavelength intervals (Wood et al 1993; Blackmer and Schepers, 1995; Whaley, 2001). New NASA satellite sensors such as MODIS and ASTER and aircraft sensors (*e.g.* AVIRIS, HYDICE) have been deployed to exploit the expanded source of information in narrower wavebands.

In addition to traditional remote sensing methods, advances in consumer electronics and the merging of photography and videography with computer technology have produced low cost camera systems that produce high quality digital images. Adamsen et al. (1999) and Kawashima and Nakatani (1998) have developed methods to assess the greenness of plants using images from digital camera equipment. Methods of estimating flower numbers have been developed using digital images (Adamsen et. al. 2000). Advances in low light video cameras have been achieved by increasing the sensitivity of the cameras in the NIR region of the spectrum. Along with tight integration of the cameras to computers, this opens the way for inexpensive devices that can produce images with good resolution in the NIR region when coupled with appropriate filters.

Hyperspectral reflectance data offer additional strategies for identifying and quantifying plant stress. Red edge position, peak characteristics, and spectral derivatives have been proposed and tested with varying degrees of success to monitor nutrient stress in plant canopies (Horler et al., 1980, 1983; Demetriades-Shah et al., 1990; Masoni et al., 1996). Neural net analysis, fuzzy analysis, and partial least squares regression analysis are powerful approaches for capturing complex functional relationships between spectra and plant properties that cannot be envisioned via usual regression techniques (Kimes et al., 1998; Jones et al., 2000). In theory, a library of spectral features could be used to make predictions regarding plant vigor, nutrient content, or pest infestations. In still another approach, linear unmixing techniques (McGwire et al. 2000) use a spectral reference library of predetermined "pure" spectral signatures (endmembers), to decompose multispectral and hyperspectral images into their component features (*e.g.* sunlit and shaded soil, healthy and stressed plant areas). Such models can be inverted to extract the amount of the whole scene that is associated with a particular stress signature. If the images are georeferenced, the stressed area can be precisely located in the field for directed sampling, traditional pest scouting, or variable rate fertilizer applications. Spectral mixing models also provide insight into how spectral properties of soils and individual plant components (leaves, stem, fruiting structures, etc.) measured with an integrating sphere or handheld spectroradiometer in the field can be scaled up to full canopy or field levels and realistically be compared with imagery acquired from aircraft or satellite sensor systems.

Crop Water Stress: Functional relationships between the TIR and plant water status have been used to define a crop water stress index (CWSI) based on canopy temperature and meteorological conditions (Idso et al., 1981; Jackson et al. 1981). One limitation of this technique is that actual plant temperature is needed, and thermal influence of the background soil can result in an erroneous estimate of water stress. Moran et al. (1994) and Clarke (1997) refined the CWSI for use under partial canopy conditions by including an estimate of percent crop cover from a vegetation index (Fig 1). In this 2-dimensional planar domain approach, the method of Idso et al. (1981) is used to predict crop canopy temperature under well-watered and water-stressed, full cover conditions (points 1 and 2, respectively in Fig. 1) and predictive equations or actual surface temperatures of a dry bare soil are used to determine point 4. Fractional vegetative cover is estimated from the NDVI using reflectance (ρ) of a 10 nm wide, NIR (790nm) and red (670nm) band:

$$NDVI = \frac{\rho_{790nm} - \rho_{670nm}}{\rho_{790nm} + \rho_{670nm}}. \qquad (1)$$

Based on the points labeled A, B, and C in fig. 1, the CWSI for a particular percent cover was calculated as:

$$CWSI = \frac{C - A}{B - A}. \qquad (2)$$

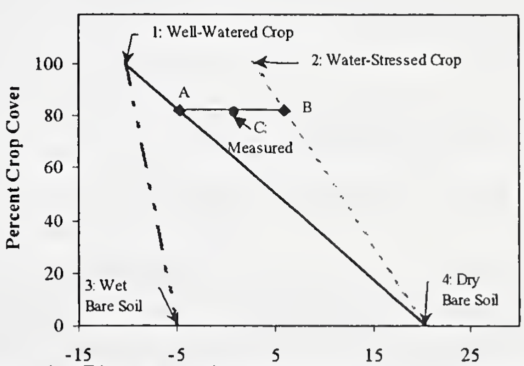

Figure 1. Diagrammatic representation of a 2-dimensional Crop Water Stress Index that compensates for varying amounts of plant cover.

Where points A and B represent the surface minus air temperature difference at a particular percent cover for a non-stressed and completely stressed crop, respectively, with a dry soil background. Points to the left of the line formed between points 1 and 4 represent a moist soil background. Since this would likely indicate a recent irrigation, no water stress is assumed under these conditions. Point C was determined based on the measured NDVI and surface – air temperature difference. From eqn. 2, a CWSI of 0 corresponds to a well-watered crop with a dry soil background, while 1 represents a water-stressed crop. The 2 dimensional CWSI has not yet been validated for quantifying plant stress during stand establishment and maturity. Establishing it as a reliable water stress index that works throughout the entire season will pave the way for its acceptance as an irrigation scheduling practice in production agriculture.

Crop Nutrient Stress: An analogous 2-dimensional index, the Canopy Chlorophyll Content Indes (CCI) that compensates for partial canopy conditions has been developed by the USWCL team for assessing the nutrient status of a cotton canopy (Fig. 2). The NDVI (eqn. 1) is used to estimate percent cover and a normalized difference red edge index (NDRE)

$$NDRE = \frac{\rho_{790\,nm} - \rho_{720\,nm}}{\rho_{790\,nm} + \rho_{720\,nm}} \qquad (3)$$

represents a spectral signal sensitive to chlorophyll pigments. Maximum and minimum chlorophyll-content limits of NDRE were defined as linear functions of NDVI and shown as solid and dashed lines on Fig 2. The CCCI was then derived using the same form as the CWSI (eqn. 2). Note that unlike the CWSI, a CCCI of 0 will typically represent a condition of crop stress (low chlorophyll content) and 1 will correspond to high chlorophyll, low stress conditions. Further testing is expected to confirm that the CCCI will be positively correlated with chlorophyll content and independent of green plant biomass during a significant portion of the growing season. Data sets will also be examined to determine if the CCCI is sensitive to the amounts of N present in storage organs of plants.

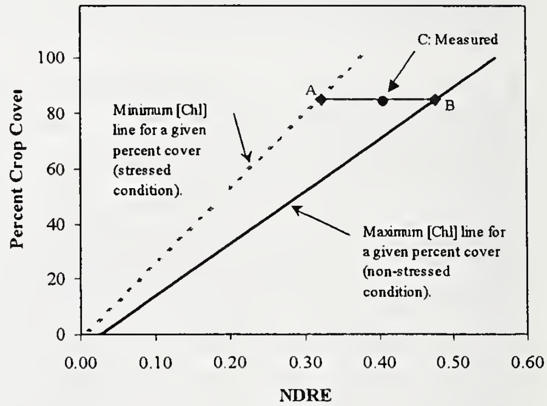

Figure 2. Diagrammatic representation of a 2-dimensional Canopy Chlorophyll Concentration Index (CCCI) that compensates for varying amounts of plant cover.

Search for Related CRIS Projects

A search of the CRIS database for "remote sensing" revealed 105 active projects within ARS and another 292 outside of ARS. Narrowing the search further to include only those projects researching areas of plant stress (i.e.,. drought, water stress, nitrogen, nutrient management, pest, insect, arthropod, weed, or disease) revealed 63 ARS and 125 non-ARS projects. A substantial amount of ARS RS research on plant response is being conducted at laboratories identified under

the **Water Resource Remote Sensing Applications Initiative** mentioned above. Our research is unique in that we recognize the confounding effects of plant biomass and phenology on remote sensing techniques and to a large extent, strive for approaches that will be useful throughout the entire growing season.

Objective 2 – Irrigation Scheduling

A fundamental requirement for accurate irrigation scheduling is the determination of the actual crop evapotranspiration (ET_c) for each day during the growing period. Past and present research of ET_c is abundant and has provided a wealth of sound theoretical knowledge, as well as major advancements in methods for estimating daily crop evapotranspiration (Doorenbos and Pruitt, 1977; Jensen et al., 1990; Allen et al., 1998). Although a number of techniques are available for estimating daily ET_c for irrigation scheduling, the crop coefficient (K_c) approach has emerged as the most widely used method (Jensen and Allen, 2000). The K_c is an empirical ratio of ET_c to a reference crop evapotranspiration (either grass or alfalfa). Standardized equation forms for computing reference ET with meteorological data have been developed, which are now highly recommended (Allen et al., 1994, Allen et al., 1998; Walter et al., 2000). A K_c curve, constructed for a crop growing period, attempts to relate the daily water use patterns of a specific crop to that of the reference crop. The K_c curve can be susceptible to inaccurate predictions of total daily ET_c, particularly for days following wetting events when the soil is not completely shaded by the crop canopy. This is because the K_c curve attempts to account for the time-averaged contributions of both crop basal ET_c (primarily transpiration) and soil evaporation following wetting events. The effects of soil evaporation on total ET_c can be calculated more accurately by using a dual crop coefficient procedure (Wright, 1982). In the dual procedure, K_c is partitioned into a separate coefficient to predict evaporation from wet soil (K_e) and a separate K_{cb} to predict the basal component of ET_c under a dry surface soil condition. Information on crop coefficients for important agricultural crops is abundant in the literature. The recently published Food and Agriculture, Paper No. 56, (FAO-56) on Crop Evapotranspiration (Allen et al., 1998) presents comprehensive procedures for constructing either the single K_c or dual (K_{cb}) daily crop coefficient curves, for use with the recommended standardized grass reference evapotranspiration (ET_o), for a large number of common agricultural crops. Two recent studies have shown that the FAO-56 dual crop coefficient procedures can adequately predict crop ET_c of cotton and grain sorghum grown in small research plots (Hunsaker, 1999; Tolk and Howell, 2000).

However, the crop coefficient curves presented in FAO-56, and generally those included with most state-of-art irrigation scheduling programs, are time-based and therefore lack the flexibility required to capture abnormal crop development and water use patterns caused by weather anomalies, insect damage, disease, or other influences (Bausch and Neale, 1989). Furthermore, using crop coefficient curves from the literature will usually require some form of locality adjustment, unless specifically developed for the particular location. Determination of actual ET_c under conditions when limitations (e.g., water, nutrient, crop density, and pest) on crop growth are encountered is particularly difficult using conventional crop coefficient procedures. Within a given irrigated cropping system, occurrences of spatially and temporally variable crop water

fluxes are often created by a variety of factors, for example, non-uniformities of water application, soil water holding characteristics, nutrient availability, stand density, and micro climatic conditions. Because a crop coefficient curve is designed to estimate the ET_c under optimum agronomic conditions, the effects of spatial and temporal variations of water use within a field or area cannot be adequately accounted for in irrigation scheduling decisions.

Remote sensing techniques offer a means to overcome many of the shortcomings of conventional crop ET estimation by providing real-time feedback of daily crop water use as influenced by actual crop developmental patterns, local atmospheric conditions, and field spatial variability. Such information when obtained on a timely basis could enable growers to more adequately assess whether changes in irrigation management strategies are warranted; e.g., changing irrigation frequency to avoid critical soil water deficits or improving irrigation system uniformities to provide sufficient water at lower ends of fields. A technique for determining total daily ET_c directly using one time-of-day RS measurements was introduced by the USWCL in 1983 (Jackson et al., 1983). Later, Inoue et al. (1994) developed a new concept for applying the technique for estimating actual transpiration and demonstrated that the method may give reliable transpiration estimates. The one-time-of day RS technique for estimating water use appeared promising at the time. However, development of the method for irrigation scheduling purposes has not been practical due to the requirement of daily ground and RS measurements and the inability to obtain reliable ET estimates on cloudy days.

Recognizing that the seasonal trajectory of multispectral VIs was very similar to the time course of wheat crop coefficients, USWCL RS scientists proposed their potential use for this purpose more than 20 years ago (Jackson et al. 1980). Implementing VI-based crop coefficients within irrigation scheduling procedures could potentially be more successful and far-reaching than other RS methods, because of the widespread familiarity and use of the crop coefficient methodology. In addition, VI data can be routinely measured either on the ground, in the air, or by spacecraft. Determining daily crop ET with VI-based crop coefficients would require frequent, but not daily, VI measurements, since the smooth general shape of the crop coefficient curve over a growing season would allow data to be extrapolated over a short period of perhaps two or three days. The VI-based crop coefficient concept of Jackson et al. (1980) later was proven a viable approach for corn in Colorado by Bausch and Neale (1987) and Neale et al. (1989). Bausch and Neale (1989) and Bausch (1995) then incorporated VI-based crop coefficients for use in existing irrigation scheduling algorithms for corn and reported improvements due to better estimation of water use and more appropriate timing of irrigations. Only limited research has been conducted to expand the development of VI-based crop coefficients for other crops, although simulation studies suggest that VIs could be used to obtain crop coefficients for several other important agricultural crops (Choudhury et al., 1994).

Search for Related CRIS Projects

A search of the CRIS system for "remote sensing" and "evapotranspiration" or "evaporation" revealed 32 active projects coded under these topics, twenty of which are within ARS. Of the 32, about 12 projects (6 within ARS) address the application of RS and ET technologies for irrigated crop water management. Only two projects pertain specifically to the development and

use of multispectral crop coefficients for improving on-farm irrigation scheduling, although several projects are attempting RS approaches for assessing temporal and spatial differences in evapotranspiration. Research on multispectral VI crop coefficients for orchard and vegetable crops are being planned by the ARS facility in Parlier, California. There is also continued research of VI-based crop coefficients by ARS in Fort Collins for crops grown in Colorado. Development of VI-based crop coefficients for use in the FAO-56 dual crop coefficient procedures is unique to this project, as is the development and application of the 2-dimensional CWSI as reliable tools for assessing crop water stress and guiding irrigation scheduling decisions.

Objective 3 – Precision Agriculture

Three levels of complexity will be pursued in adapting remotely sensed data for use in precision farm management: (1) directed sampling (i.e., use of a single image to spatially interpolate crop attributes measured at locations identified by analysis of the image); (2) combination of simple empirical models (e.g., based on growing degree-days) and remotely sensed data to estimate crop water and nutrient status; (3) integration of remotely sensed data with process-oriented growth models. Note that in this section the background information for levels 2 and 3 are combined under the sections on growth models and approaches to integrate remotely sensed data with these models.

Directed Sampling

Rather than relying on a specific spectral response to a particular soil property, the concept of "directed soil sampling" has been developed (Pocknee et al., 1996). The idea is to first acquire imagery of a bare soil field and then take soil samples from areas in the image with distinct spectral features. Correlations or classification schemes are then developed between the spectral classes or reflectance levels and soil properties of interest. Pocknee et al. (1996) found this method worked well for mapping soil phosphorus, but performed poorly for soil pH. Directed soil sampling can often provide soil maps of similar or better accuracy than those derived from interpolation techniques such as kriging or distance-weighted interpolation with even fewer soil samples (Thompson and Robert, 1995; Barnes and Baker, 2000). A similar approach can be used over fields with a crop present by collecting soil samples and plant material for analysis over areas with similar spectral classes (Yang and Anderson, 1996; Barnes and Baker, 2000). Statistical methods have been developed to assist in the process of selecting sample sites based on the observed spatial variability in soil electrical conductivity within a field to allow the most accurate interpolation (Lesch et al., 1995); however, these methods have not been tested with multispectral data. While directed sampling has been found useful in mapping variations in soil and crop properties, Barnes and Baker (2000) found that a number of interfering factors can compromise such an approach.

Crop Growth Models

Crop growth models have been developed with various levels of sophistication (Penning de Vries et al., 1989). First level models only respond to variations in temperature and radiation.

Level 2 models include some type of soil water balance to integrate moisture stress into the growth predictions. Level 3 models add simulation of the effects of nitrogen availability, while level 4 models address additional stresses such as weed pressure and insect infestations. All growth models require some level of calibration before they can be applied with confidence (Kenig et al., 1993) because a purely deterministic model has yet to be developed. Most process-oriented growth models predict the level of photosynthesis based on weather conditions, photosynthetically active biomass and the availability of resources such as water and nitrogen. Photosynthesis is then partitioned between maintenance and growth respiration based on the crop's predicted development stage (see reviews by Jones and Ritchie,1990; and Hoogenboom et al., 1992). The output from several models have been incorporated with economic and decision support tools in order to enhance their use in farm management decisions. For example, a Decision Support System for Agrotechnology Transfer (DSSAT) has been developed to automatically search for agricultural management optimization strategies based on various objective functions (Tsuji et al., 1994). DSSAT incorporates models of cereal, legume and root crops into a common system and uses an internationally standardized format for data input and predictive output (IBSNAT, 1986). Linkage with GIS has allowed crop models to be applied to regional studies (Lal et al., 1993).

With the increased use of geospatial tools in farm management, efforts began to adapt crop models to predict within field production variability. The earliest efforts, as reviewed by Sadler and Russell (1997), focused on running the models at grid points or management zones within a field. The results for this approach has had mixed success in adequately describing spatial variability in crop development and the input data requirements were dramatically increased. Another approach has been to form a hypothesis as to the parameters in the model most closely associated with the major source of yield variability. The model is then run and used to identify parameters until the error between simulated and observed yields are minimized (Paz et al., 1998). If the major source of yield variability is temporally constant, this procedure then provides a set of spatially associated input parameters for use in future growing seasons.

Integration of Remotely-Sensed Data and Growth Models

Limitations to the use of yield maps for model calibration are that they do not provide a means to assess a model's performance or supply inputs during the growing season and all sources of variability are integrated in the yield response. For example, from a yield map alone it is not possible to determine if a relative decrease in production is related to insect damage, soil properties or weeds. Remotely-sensed data have the advantage of determining spatial variability in crop canopy density during the season. While it may not always be possible to determine the source of variability solely from imagery, field scouting can reveal the source near the time it occurs.

The potential for the integration of remotely sensed data with growth models was suggested over 20 years ago (Wiegand et al., 1979). Maas (1988) identified four approaches for the integration of models and remotely sensed data that can further be reduced to two basic methods: (1) input a remotely estimated state variable (e.g., LAI) directly into the model at each time step or forcing agreement at selected times during the season, and (2) adjustment of the model's initial

conditions and/or parameters until the model's predictions are in agreement with remotely sensed estimates. Moulin et al. (1998) provided a review of several of the integration approaches that have been recently developed. Such approaches have been adapted for simple, empirical models (Potdar, 1993; Raun et al., 2001) to the integration with more process-oriented models. Raun et al. (2001) developed a yield forecast model based on early season NDVI and growing degree-days for real-time application of nitrogen. Moran et al. (1995) used remotely sensed estimates of ET and LAI in the real-time calibration of a simple alfalfa and water balance model. This is a unique approach, in that the alfalfa model's predictions are compared to the remotely-sensed estimates and then the model is iteratively adjusted until both estimates are in agreement. Lo Seen et al. (1995) investigated methods to integrate remotely sensed measurements into a grassland production model. The grass production model is a simple level 2 model, modeling growth and the water budget. The analysis of several vegetative indices derived from AVHRR data found that the NDVI and Soil Adjusted Vegetation Index (SAVI) were capable of tracking vegetation development. Barnes et al. (1997) demonstrated the feasibility of inputting remotely sensed estimates of LAI at select times during the season to allow the CERES-Wheat model to predicted nitrogen limited conditions when data was not provided to the model to indicate N deficiency. Similarly, Barnes et al. (2000) also found that the CWSI has potential to adjust the soil-water content predictions of CERES-Wheat to account for water limited conditions. Jones and Barnes (2000) adjusted the soil water holding capacity parameters in the cotton model CALGOS until the model was able to correctly predict LAI during the season for two soil types.

Search of Related CRIS Projects

There is a large number of CRIS projects coded for "remote sensing" and crop modeling – 23 ARS and 18 non-ARS. Of these 41 projects, 26 were not related directly to crop management (i.e., they were focused on prediction of large area yields, water quality parameters, or climate change). The remaining 15 that did have a similar scope to this objective were primarily projects in the Midwest and Eastern United States in non-irrigated conditions and for usually directed towards different crops (primarily corn and soybeans).

National Collaboration

All objectives for this project relate directly to the Water Resource Remote Sensing Applications Initiative in NP201 which will develop cost-effective methods to assess soil, water, and plant conditions and technologies for improved management at field, farm, and watershed scales. The Initiative's research is geared towards providing timely RS solutions to water quantity and quality problems impacting production agriculture, ecology and the environment. We envision all aspects of our research as being complementary to ARS research at Beltsville MD, Bushland TX, El Reno OK, Florence SC, Fort Collins CO, Parlier CA, Kimberly ID, Lubbock TX, Shafter CA, Tucson AZ, and Weslaco TX. Although collaboration with these research groups is not essential in order to complete the research described herein, collaborative interactions will serve to accelerate development, broaden regional applicability, and improve robustness of methods that are useful for major US cropping systems. Under the coordination of National Program Leadership, ARS scientists doing remote sensing research are expected to convene biennially to

discuss methods, problems, and research findings of mutual interest.

APPROACH AND RESEARCH PROCEDURES

The overall goal of this project is to develop and test remote sensing approaches that will prove useful in short- and long-term management of agriculture resources. As stated above, the proposed research is organized into three objectives, crop response, irrigation scheduling, and precision agriculture, each of which are described below:

Objective 1 - Crop Response

Develop and critically assess methods for using reflected solar and emitted thermal energy to quantify temporal and spatial variations in crop response to water, nutrients, and pests.

Hypotheses for Objective 1:

1. Environmental stresses that limit productivity of agricultural crops can be detected and quantified by means of observable changes in their spectral properties.

2. Identification of water and nutrient related stresses during periods when plants do not completely cover the soil surface can be improved by combining traditional vegetation indices such as the NDVI with spectral information that does not vary as much with canopy biomass.

Experimental Design

During the initial phase of this project, we plan to develop and refine remote approaches for monitoring crop response using full-season data of numerous RS, soil, and agronomic measurements acquired during previous USWCL experiments in alfalfa, cotton, wheat, and vegetables (*e.g.*, Barnes et al 1996, 2000; Moran et al., 1989,1995; Hunsaker et. al., 1994, 2000; Kimball et. al., 1994, 1999; Pinter et al. 1994, 2000). We will develop a detailed knowledge base of plant spectral reflectance and emittance characteristics for crops growing under optimum water and nutrient conditions. The RS data will be transformed into wide- and narrowband reflectance factors, multispectral vegetation indices, physiological reflectance indices, and other spectral features which, based on RS team experience and reports in the literature, appear most sensitive to plant growth and stress parameters. Correlations between these spectral indicators will identify those which contain redundant information and those which contain unique information. Regression techniques will be used to identify functional relationships between RS signals and properties related to normal and stressed vegetation properties. Emphasis will be placed on further testing and validation of 2-dimensional CWSI and CCCI indices for estimating water and nutrient stress in cotton and wheat throughout the entire growing season, including the stand establishment phase when early detection of stress can have a large influence on a grower's ability to achieve maximum economic yield. Hyperspectral approaches for identifying stress will be explored using neural net, fuzzy analysis, partial least squares regression, and linear mixture modeling techniques.

New experimental data will be obtained from a series of intensive, season-long, interdisciplinary field plot experiments in cotton and wheat. Data from these experiments will serve as a mechanism for evaluation, refinement, and validation of RS irrigation scheduling and crop modeling techniques. Recognizing the limited human resources for this project, these experiments will be coordinated and conducted by the entire RS team in a concerted effort to meet many of the various goals sought under each of the three primary project objectives. We also plan to be opportunistic in our research. For example, if a proposed Free Air CO_2 Enrichment (FACE) experiment in alfalfa is funded by NASA, we intend to make regular RS observations on alfalfa exposed to different CO_2 and water stress treatments, while cooperators obtain agronomic, physiological, and other measurements.

Small Plot Procedures: Upland cotton (*Gossypium hirsutum* L.) and spring wheat (*Triticum aestivum* L.) will each be grown for two seasons in small (1.5 ha), level basin fields at The University of Arizona Maricopa Agricultural Center (MAC) during 2002 and 2003 (cotton) and 2003-04 and 2004-05 (wheat). Each experiment will include a two by three factorial consisting of two nitrogen levels (high and low) and three plant population densities (standard practice, high, and low). The experiments will also include two additional treatments both managed at high nitrogen and standard plant density. The latter two treatments, as well as irrigation scheduling procedures for all treatments, will be described later in the Approach and Procedures section under Objective 2. All treatments will be replicated four times in plots approximately 15 by 30 m. For the cotton studies, seed from a full season, commercial cultivar will be sown on raised, east-west oriented beds spaced 1.02m apart during the normal April planting window. For wheat, seed from a locally adapted cultivar will be sown on the flat during the normal December planting window. The three plant populations will be achieved using precision planting equipment and seeding rates corresponding to 2x, 1x, and 0.5x the recommended rates for each crop. The high N treatment will be managed according to recommended MAC farm nitrogen practices for the crop to achieve full yield potential while the low N treatment will receive an amount calculated to reduce yield by about one-third.

Meteorological Data: Hourly and daily weather data are available from the automated Arizona Meteorological Network (AZMET). The AZMET weather station at MAC is located over a well-irrigated grass plot, less than 1 km away from the small plot basins. Data from this station will be used to calculate the FAO-56 reference ET_0 needed for irrigation scheduling as described in Objective 2, Goal 2. Portable weather stations will provide backup weather data in the field. Micrometeorological sensors (*e.g.,* thermocouples, psychrometers, pyranometers, net radiometers, IRTs, etc.) will be deployed in specific plots as needed to achieve specific objectives and for comparison with AZMET station data.

Soil Measurements: The concentrations of nitrate and ammonium throughout the rooting zone will be determined in 300 mm increments before and after the cropping cycle and as needed during the growing season. All plots will receive sufficient N and P to meet recommended preplant requirements. Neutron scattering access tubes and time domain reflectometry (TDR) probes will be installed in each plot to measure soil water status during the season. Irrigation to plots will be provided through a metered, gated-pipe irrigation system (see Approach Objective

2). A salinity map of the field will be made using a tractor-mounted EM-38 system. Data from this map will be used to guide soil sampling. Soil will be analyzed for salinity, moisture and texture as well as other soil properties that may have contributed to variability of EM-38 data.

Plant Measurements: Relevant agronomic parameters (*e.g.*, stand density, phenological development, biomass, leaf area index, and final yield) will be evaluated from destructive sampling at appropriate intervals throughout the season. The nitrate content of the petioles of cotton and the lower 50 mm of stem tissue from wheat will be determined and compared with SPAD readings throughout the growing season. Plant water status will be assayed periodically using pressure bomb, porometry, and stem flow techniques. Plant area index will be monitored at 1-2 week intervals with a LAI-2000. Estimates of fAPAR will be determined using a line quantum sensor or inferred from VI-based relationships developed in previous experiments (Pinter et al., 1994).

Remote sensing: Measurements will be made at the whole canopy level from planting until harvest using (1) wideband radiometers (visible and NIR), (2) high resolution spectroradiometers (visible, NIR, SWIR) region (~350 to 2500nm), and (3) infrared radiometers (10-12 μm). Reflectance and transmittance measurements will be made at the single leaf level using an artificial light source, an external integrating sphere, and high resolution spectroradiometers. Temporal trends in broad-band reflectance factors, multispectral vegetation indices, hyperspectral features (*e.g.* spectral derivatives, red edge position), and canopy temperatures will be critically examined at the single leaf and canopy level for information that can be used to quantify plant water, nutrient, and pest stress. Advances in sensor technology and emergence of new techniques (*e.g.* appropriately filtered, 3-CCD digital cameras) may provide additional opportunities for obtaining spectral data.

Team Responsibilities

Research conducted under Objective 1 (Crop Response) will be under the direction of Paul Pinter. Each scientist will assume responsibility for measurement and analysis of one or more unique aspects of the experiment in which he has expertise. Integration of the various parts and collaboration between team members will be necessary to achieve the stated goals. Paul Pinter for example, will coordinate biological measurements and be responsible for developing relationships between wide- and narrow-band spectral reflectances and various agronomic, biophysical, and stress-related responses of the plant canopy. Ed Barnes and Tom Clarke will focus their attention on measuring necessary parameters and refining and validating the 2-dimensional CWSI and CCCI indices described earlier. Glenn Fitzgerald brings special skills in mixture modeling and image analysis to bear on analyzing the high resolution image and radiometric data obtain from the field experiments and correlating them with specific plant stresses. Doug Hunsaker will be responsible for measuring soil moisture levels and along with Bruce Kimball will evaluate evapotranspiration by various methods. Floyd Adamsen contributes expertise in analysis of digital imagery plus broad experience in managing nutrients in agricultural systems. Gary Wall will be responsible for measuring and interpreting whole plant water relations within the context of irrigation treatments.

Contingencies

As in most scientific research, both positive and negative findings will be useful in delineating realistic opportunities and limitations for using RS in crop management. We recognize that a number of exogenous factors affect remotely acquired reflectance and emittance data although they are not related to soil or crop properties of interest. (*e.g.*, illumination and sensor viewing direction, clouds, droplets of precipitation on vegetation, etc.). Bidirectional models of canopy reflectance will be examined to determine their utility for normalizing data to standard conditions. Thermal indices for evaluating soil water content are likely not to provide useful information when evaporative demand is low, and the CCCI might not be sensitive to plant-stored N. Thus special attention will be paid to defining conditions under which the indices do not perform as expected and guidelines will be developed to minimize their impact. If simple reflectance-based indices of crop vigor do not provide sufficient detection resolution for a particular plant stress or distinguish between different stresses, multivariate analysis incorporating hyperspectral reflectance or wideband thermal data will be used to improve performance.

Collaborations

Necessary (within ARS) - Susan Moran at Tucson AZ (Remote estimates of ET, instrumentation, and calibration). Scientists at a number of ARS locations are actively pursuing spectral reflectance techniques for detecting nutrient stress (Beltsville MD, Fort Collins CO, Lincoln NB), water stress (Bushland TX, Florence SC, Lubbock TX) and salinity stress (Riverside CA). Project scientists anticipate discussing research approaches, comparing techniques, and continued interaction with these related projects. As mentioned above under National Collaboration, ARS also recently brought together these and other ARS scientists who are involved in various aspects of remote sensing research. Bi-annual meetings, workshops, shared resources, and joint publications with this group will increase awareness of other projects and new avenues of cooperation will evolve.

Necessary (external to ARS) - Jiaguo Qi with Michigan State University (BRDF and calibration issues)

Objective 2 – Irrigation Scheduling

Develop and improve irrigation scheduling methodologies that are responsive to actual crop evapotranspiration and irrigation requirements.

Hypotheses

1. Multispectral crop coefficients will provide improved irrigation scheduling and water management capabilities as compared to more traditional crop coefficients that are usually based on time or thermal units after planting.

2. Multispectral crop coefficient models used in conjunction with the 2-dimensional CWSI, can accurately quantify real-time crop water use and its spatial variability.

Experimental Design

Research under Objective 2 is expected to expand the development of remote sensing measurement tools and procedures for guiding irrigation scheduling so that they match actual crop and environmental conditions more closely. We have divided this research into three goals. Goal 1 will be to develop working basal crop coefficient models based on multispectral VIs for primary crops grown in the region - alfalfa, cotton, wheat, and grain sorghum. For Goal 2, small-plot field studies will be undertaken to examine and validate the VI-based crop coefficient models for scheduling proper irrigation amounts to cotton and wheat. In conjunction with the VI-based crop coefficients for irrigation scheduling, we will refine and validate use of the 2-dimensional CWSI for determining appropriate irrigation timing for cotton and wheat. The small-plot experiments will also be designed to include the necessary data for field validation of the one time-of-day direct RS technique for determining actual crop evapotranspiration. Goal 3 will be to evaluate the use of multispectral crop coefficients and thermal indices to provide detailed information about spatial variations of crop water use within large surface-irrigated fields. Such information would ultimately allow growers a means to more adequately appraise the water needs and irrigation requirements within their fields.

Goal 1. During the first year of the project (2001 to 2002), we will analyze and develop initial multispectral basal crop coefficient models and related algorithms using data from past experiments conducted by the USWCL, in which both ET and reflectance measurements were made for crops grown under well-watered and well-fertilized conditions (e.g., data from Hunsaker et al., 1994; Kimball et al. 1994; and Pinter et al., 1992, 1994, for cotton: and from Hunsaker et al., 1996, 2000; Kimball et al. 1999; and Pinter et al., 2000, for wheat). The K_{cb} values for these initial models will be derived following procedures similar to those developed by Hunsaker (1999).

Goal 2. Field demonstration and validation of the VI-based K_{cb} models for irrigation scheduling will take place during the two-year, small-plot experiments planned for cotton (2002 and 2003) and for wheat (2003-2004 and 2004-2005). General experimental design procedures, treatments, and description of field measurements for these studies are described above in Objective 1. All experiments will include six treatments used to test VI-based K_{cb} under three plant densities (high, standard, and low) and two soil nitrogen levels (high and low). These experiments will also include a control treatment, grown under a standard plant density and a high nitrogen application, in which irrigation scheduling will be determined using the dual crop coefficient procedures recommended by FAO-56 including the daily basal crop coefficient curve for the crop recommended in FAO-56. A final treatment (water-stressed), also grown under a standard plant density and a high nitrogen application, will be included in each experiment to provide data needed for assessing the suitability of the 2-dimensional CWSI as a reliable indicator of the effects of water stress on actual ET_c reductions, and as a practical irrigation timing tool. Irrigation scheduling for the water-stressed treatment will follow the same procedures as that for the control treatment, with the exception that three irrigations during the season will be delayed

to impose greater soil water depletion and water stress on the crop. Irrigation for the six VI-based K_{cb} treatments will be scheduled using the dual crop coefficient procedures of FAO-56. However, for these six treatments, the multispectral K_{cb} model will be used to determine the daily K_{cb} of each treatment using reflectance field measurements. For determining the irrigation amounts for all treatments, the soil evaporation component of total crop ET will be estimated using the explicit procedures of FAO-56, including their recommended soil evaporation drying parameters for the specific soil type used in the field studies. Plots within several treatments will be monitored to effectively evaluate the direct measurement of ET_c using the one time-of-day RS technique.

Irrigation scheduling based on remote vegetation indices may be less successful early in the season when plants are small, during cloudy weather, or when the water holding capacity in the rooting zone is limited. Thus, during the first-year experiment for each crop, we may find it necessary to periodically update the K_{cb} for some treatments if the initial VI-based K_{cb} model is determined to be performing poorly. Such adjustments would be made on the basis of actual ET_c determined by frequent soil water content measurements. The second-year experiment for each crop will serve to confirm whether or not the original K_{cb} model, or perhaps a refined K_{cb} model - i.e., a model based on data from the past experiments combined with additional findings from the first-year experiment of this study, accurately predicts ET_c under all conditions imposed on treatments. Performance evaluation of the K_{cb} models will be primarily based on comparison of the model-predicted ET_c against actual ET_c determined by detailed soil water content measurements, but will also include evaluations based on actual crop performance as determined from measurements of crop growth during the growing period and final yields. In all experiments, performance of the multispectral K_{cb} model for the treatment under standard plant density and high nitrogen will be compared to that of the control treatment to assess whether the multispectral crop coefficient model provides significant improvement over the FAO-56 K_{cb} curve for irrigation scheduling.

Although not necessary to complete the research outlined here, mutual exchange of multispectral K_{cb} development techniques and/or data is expected to occur with the ARS investigators in Fort Collins (D. Heermann, W. Bausch), Kimberly (J. Wright), and Parlier (T. Trout), who have completed or are planning to conduct similar research. If the FACE alfalfa field experiment is funded by NASA during this project's time-span, we plan to utilize the experiment as a means to field-test the alfalfa K_{cb} model that will be developed in Goal 1 of this objective.

Goal 3. Evaluation of VI-based crop coefficients and thermal indices as tools to detect and quantify field-scale spatial variability of crop water use will be undertaken in 2002 during studies planned on a large, production-size cotton field, described below in more detail in objective 3. After the first aerial image (figure 3) of the field is made at about 35-50% crop cover, the directed sampling approach described in objective 3 will be used to identify three distinct areas within the field at which ET_c rates are potentially different (e.g., high, medium, and low rates). Neutron access tubes and TDR probes will then be installed within each of the three identified areas to measure soil water content. During the course of the season, additional aerial images of the field will be obtained at the end of each irrigation cycle, just before the next irrigation is applied. Thus, measurements of VI and thermal indices will be provided during the

course of the growing season at the three identified areas. Predicted cumulative ET_c over each irrigation cycle during the remainder of the season will be calculated using measured VI data to develop a time-averaged K_{cb} curve over each irrigation cycle for each area. The K_{cb} model developed in the small-plot studies for cotton will be used to determine the K_{cb} values. Thermal indices obtained from the images will also be used to detect differences in crop water status. Measurements of soil water made during irrigation cycles will provide data to quantify differences in actual crop water use among the areas, as well as information on the actual soil water status within the areas.

Team Responsibilities

Research under Objective 2 will be largely under the direction of Doug Hunsaker. He will be responsible for detailed elements of experimental design; measuring, and analyzing soil water contents; estimating ET; and scheduling specific irrigation events. Doug Hunsaker and Paul Pinter will be responsible for developing multispectral K_{cb} values for cotton, wheat, and alfalfa from historic USWCL data sets. Floyd Adamsen will measure and analyze soil and plant nitrogen concentrations. Tom Clarke will handle micrometeorological measurements. Ed Barnes and Glenn Fitzgerald will provide support in image collection and analysis. Bruce Kimball and Gary Wall will provide expertise in determining ET and measuring plant water relations, respectively.

Contingencies

The initial multispectral K_{cb} models developed in goal 1 will be tested during the cotton and wheat small-plot irrigation scheduling experiments. As mentioned under goal 2, these initial K_{cb} models may not perform well under certain conditions during the season and it may be necessary to occasionally adjust the K_{cb} for some treatments during the season. Furthermore, the initial spectral K_{cb} models for cotton and wheat will be developed from past studies in which the crops were grown under sub-surface drip irrigation. Thus, there may be transferability problems associated the models when applied to surface irrigated systems. In the event that the initial K_{cb} models for either or both crops are deemed to be completely inappropriate, we would plan to conduct the second-year experiment with a redeveloped model. In this event, the model would be highly dependent upon the data obtained from the first-year experiment. For the field plot experiments, there is a slight possibility that abundant rainfall may preclude the development of a highly water-stressed treatment.

Collaborations

ARS locations presently engaged in research activities related to irrigation scheduling and the development of crop coefficients include Bushland TX, Fort Collins CO, Kimberly ID, Parlier CA. While formal collaboration is not essential for conducting research under this objective, we interact with the scientists at these locations via the ARS Remote Sensing Workshops. We also work closely with national scientists involved in this area through representation (D. Hunsaker) on the ASCE Committee on Evapotranspiration in Irrigation and Hydrology.

Objective 3 – Precision Management

Develop methods for using remotely sensed observations in precision management of water, nutrients, and pests in irrigated crops.

Hypotheses

1. The statistical sampling approach developed by Lesch et al. (1995) for EM-38 salinity maps can be adapted for multispectral and TIR imagery to generate maps of crop density and conditions related to water, nutrient, and pest stresses.

2. The spatial extent and location of management zones identified from RS imagery will not be consistent during the growing season.

3. Techniques developed under Objectives 1 and 2 (*i.e.*, VI-based crop coefficients, improvements in the 2-dimensional CWSI, and estimation of nitrogen status from the CCCI) can be used to quantify natural variability in crop condition in a production field.

4. The combination of a growing degree day parameter with the CCCI will allow accurate determination of crop nitrogen status throughout the growing season with a single set of calibration coefficients.

5. Integration of the CCCI, multispectral K_{cb}, and 2-dimensional CWSI will provide a comprehensive water and nitrogen management method for crop management purposes.

6. RS estimates of crop water condition, nitrogen status, and fAPAR can improve the ability of process-oriented crop models to predict spatial variability across a field or farm.

Experimental Design

Directed Sampling

At the same time as the cotton field plot studies in 2002 (Objective 2, Goal 2), a separate experiment will be conducted in a commercial sized cotton field to develop methods for using remote imagery to optimize field sampling. Aerial imagery will be acquired at planting and then at approximately two-week intervals once the crop has reached ~35 to 50% cover. We intend to use an imaging system having visible, NIR, and thermal capabilities that was designed and assembled by RS Team scientists and deployed successfully over MAC fields during early June 2001 when cotton plant cover was <10%. Examples of imagery obtained with this system are shown in figure 3.

Consistent spatial and temporal performance of RS approaches to directed sampling or precision agriculture requires careful calibration of imagery. Our protocol therefore, includes coincident ground-based radiometric observations of 8 by 8 m canvas calibration tarps (fig. 3b and Moran

et al. 2001) and other specific areas with the field. These observations are used to convert red and NIR images to reflectances from which a meaningful vegetation index such as the NDVI (fig. 3d) can be calculated. Thermal scanner performance is verified in a similar fashion using calibrated handheld infrared thermometers. The day following image acquisition, sample locations within the fields (*i.e.* ESAP points in fig. 3a) will be identified from the imagery using statistical procedures developed by Lesch et al. (1995). These procedures were originally developed for use with ground-based soil conductivity sensor data, but we have adapted them for use with a vegetation index derived from the red and NIR data. In this sampling approach, a minimum set of calibration samples are selected based on the observed magnitudes and spatial locations of the data, with the explicit goal of optimizing the estimation of a regression model (i.e., minimizing the mean square prediction errors produced by the calibration function). The regression model is then used to extrapolate predictions at all remaining (i.e., non-sampled) areas. Once the sampling points have been identified, plant and soil samples will be collected at each location using differentially corrected GPS receivers. Gravimetric moisture content and particle size distribution will be determined from the soil samples and petiole nitrate levels, LAI, biomass, growth stage, insect damage, etc. will be identified from the plant samples. Additional locations will be randomly sampled for later comparison with the methods used to classify the imagery. Two Bowen ratio stations will be installed in the large cotton field to measure ET_c continuously during the experiment. These data will be used to (1) determine what crop characteristics can be accurately interpolated using NIR, red and thermal data, (2) examine the temporal dynamics of spatial variability during a growing season, and test other approaches developed for the field plot studies identified in objectives 1 and 2 in a production-sized agricultural field.

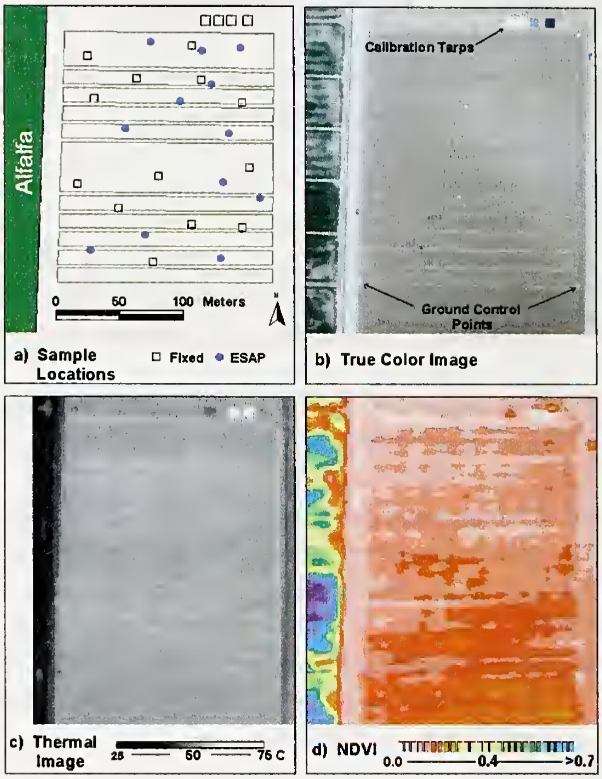

Figure 3. Images acquired at MAC with the USWCL sensor system at ~1045h on 6 June 2001 showing: a) cotton field with fixed- and statistically-selected (ESAP) sampling locations, b) color image from a Nikon digital camera, c) radiometric surface temperatures (grayscale) from an Inframetrics Model 760 thermal scanner, and d) color-enhanced NDVI from a Dycam Agricultural Digital Camera. All images were georeferenced with ERDAS Imagine using ground control points (fig. 3b). Thermal and NDVI data were calibrated using coincident radiant temperature and reflectance factors, respectively, measured with ground-based radiometers over calibration tarps and field targets.

Empirical Model Development

Secondly, procedures to integrate a simple growing degree-day parameter with the CCCI will be investigated to determine if this approach can yield acceptable predictions of nitrogen levels throughout the growing season with one set of calibration parameters. Data from previous cotton (Barnes et al., 2001) and wheat experiments (Kimball et al., 1999) will be used to formulate the calibration relationship, and then data from the small plots studies proposed under objective one will be used for validation and refinement. The next step will be to integrate this model with the water use estimates described in objective 2 to formulate a simple nitrogen and water management model driven by RS data. Additionally, for the data sets collected under objective 3, linear mixing models will be used to determine whether for additional components (e.g., shaded and sunlit soil) improves the 2-dimensional CWSI and CCCI approach.

Integration with Process-Oriented Models

Three cotton models will be investigated for integration with remotely sensed data: CALGOS (Marani et al., 1995); GOSSYM (Baker et al. 1983); and CPM (Cotton Production Model, V.R. Reddy, ARS, Beltsville MD). CALGOS was developed specifically for arid conditions; however, only limited calibration of the model for different varieties has been accomplished. GOSSYM has undergone much development in humid regions. CPM offers more mechanistic handling of energy and water relations, but it is still early in the development stages, and as with CALGOS only has parameters for a limited number of cotton varieties. The primary model for use with wheat will be the generic CERES distributed with DSSAT 3.5 (Tsuji et al., 1994). This model is chosen as it is a member of the DSSAT family and has undergone extensive validation around the world. It also contains the ability to simulate both water and nitrogen use.

For both crops, similar approaches will be used to integrate multi-spectral data obtained during the course of the growing season to provide "mid-course" corrections to the predictions of the growth models. Previous studies by the investigators have found RS estimates of leaf area index (LAI) to be useful in model adjustments (wheat, Barnes et al., 1997; cotton, Jones and Barnes, 2000). In addition to LAI, remotely sensed estimates of fAPAR will be used in the adjustment procedures, as this estimate has been found to be more robust than LAI for different solar zenith angles and crop conditions (Pinter et al., 1994). Further study will also be given to the use of the CWSI to evaluate the model's estimate of crop water status (Barnes et al., 2000).

The first procedures to be developed will be based on the assumption that the resources limiting growth below potential after accounting for climatic conditions are known (e.g., water and nitrogen). Once identified, the model's initial conditions and parameters related to the limiting resources will be adjusted iteratively in order to provide a match between the model's prediction and remotely sensed estimate. Rather than assuming the model is "wrong" and the remotely sensed estimate "right," uncertainties will be assigned to both estimates. In the case of remotely sensed data derived from empirical relationships, the prediction interval could be used. Ideally, the model's prediction interval can be established if previous year's data is available with field observations; however, in an actual application to farm management, such data may not always be available. Therefore, other numeric techniques such as fuzzy number theory will be

evaluated to describe uncertainties and define approaches to weight these uncertainties so that the best estimate of actual conditions is determined using information from both the model and RS estimates.

The application of these procedures to cotton will begin by evaluating the three models to simulate existing cotton data sets collected at MAC. A total of seven seasons of growth data are currently available for this site (Pinter et al., 1994 - 3 seasons; Barnes et al., 2001 - 2 seasons and two years of unpublished data). Data collected during the experiments discussed in objective 2 will be critical for validation of the procedures. For wheat, four seasons of data are available (Kimball et al., 1999) for evaluation of the integration procedures as will be the data collected under objective one in the wheat experiments.

Team Responsibilities

The field and modeling research conducted under Precision Agriculture - Objective 3 will be carried out under the direction of Ed Barnes who will be responsible for day to day operation and coordination of the project, scheduling the field cultural activities, image analysis, GPS georeferencing observations, and model integration. Glenn Fitzgerald and Tom Clarke will be responsible for preparing the sensor package used in the aircraft, collecting, and downloading and analyzing image data. Glenn Fitzgerald will provide expertise in spectral modeling approaches used to scale single leaf and canopy component spectral properties up for comparison with larger scale aircraft and satellite imagery. Tom Clarke and Paul Pinter will coordinate the vicarious ground calibrations at time of overpass. Paul Pinter will provide and interpret RS data sets from previous USWCL experiments that will be used in model integration, and coordinate biological observations during the experiments. During the directed sampling experiment, Doug Hunsaker will quantify soil texture and soil moisture parameters while Floyd Adamsen will be responsible for measuring and analyzing soil and plant nutrient concentrations.

Contingencies

In the event that the statistical sampling procedures developed by Lesch et al. (1995) for use with EM-38 derived salinity maps do not provide satisfactory results when adapted for use with a vegetation index, unsupervised classification techniques will be used with a maximum likelihood decision rule to define spectral classes in the field. Samples will then be taken from areas representing each spectral class similar to the procedures used by Yang and Anderson (1996). In certain situations, such as early season nutrient stress detection mentioned in Objective 1, remotely sensed data may not be able to improve a model's performance. When reliable techniques cannot be developed using RS data for within season adjustment of crop models, efforts will focus on characterizing the input information needed by the models (e.g., spatial extent of soil types, zones having similar crop response from previous seasons' imagery, etc.). In the event other scientists at the USWCL decide to continue development of the $COTCO_2$ model (Wall et al., 1994), this model will be added to the suite of cotton models evaluated for potential integration with RS data. In the event NASA funds an alfalfa study, further refinement of the PROBE model (Moran et al., 1995) will take place.

Project scientists are mindful of scaling issues encountered when quantitative techniques based on ground measurements are implemented at the field and farm level using aircraft or satellite data. Recent addition of a new team member (G. Fitzgerald) and his specialized skills in spectral mixing models are expected to provide additional insight into how spectral properties of soils and individual plant components (leaves, stem, fruiting structures, etc.) measured with an integrating sphere or handheld spectroradiometer can be scaled up to full canopy or field levels and realistically compared with imagery acquired from aircraft or satellite sensor systems. Spectral unmixing techniques can be used to address the disaggregation approach. We have also specified the technical requirements and recently contracted for the purchase of a hyperspectral imaging system utilizing liquid crystal tunable filters which is expected to provide an additional investigative approach for this research.

Remotely acquired data are also inherently discontinuous in time. Simple averages of occasional canopy reflectance factors or midday temperatures are not likely to be the best approach for crop management. It is for this reason that we believe the combination remote sensing and modeling approach mentioned in Objective 3 will be so powerful. Mechanistic models, governed by physical processes, driven by more or less continuous meteorological parameters, and occasionally given a reality check, tune-up, or re-parameterization with remote observations will likely provide an effective way to use remotely sensed data for management purposes.

Collaborations

Necessary (within ARS) - Scott Lesch (ARS, Riverside CA) will provide assistance in efforts to adapt his statistical methods to determine within field sample locations with electrical conductivity data to reflectance-based indices.

Necessary (outside ARS) - The integration of RS and crop simulation models will be investigated in cooperation with Dr. J. Alex Thomasson, University of Mississippi with ARS in Stoneville MS. Dr. Thomasson has compiled a team of scientist engineers, an economist and extension specialist to assist in development of these approaches for cotton, including Dr. James McKinnon with ARS who was one of the original developers of GOSSYM. Shared data sets between the two locations will allow evaluation of the techniques under diverse growing conditions. David Jones, University of Nebraska, Lincoln will provide technical expertise on the application of fuzzy number theory to describe uncertainties.

Project scientists recognize that official involvement with the regional committee - NCR 180 “Precision Agriculture” would also be very beneficial to our program. There are a number of participating states that have a large irrigated agriculture component and thus are dealing with many of the same precision agriculture management issues. In particular, NCR 180 is addressing the need for quality, timely, and readily available remote images for scouting field problems, predicting yields, monitoring crop quality, making management decisions, and identifying crop management zones. We presently interact with several of the active members of this committee, and plan to participate in their annual meetings. Another potential point for cooperation involves the Ag 20/20 Project which is a partnership between NASA, CSREES, and

various national commodity groups. We have used their listing of top management requirements for cotton and wheat to help focus our research on areas that commodity groups think are most important. Our current projects do not meet the criteria for formal involvement in Ag 20/20 (*e.g.* commercially available imagery, large scale fields, yield monitors), but their objectives and goals are very similar to our own and we intend to remain peripherally involved with that project.

Physical and Human Resources

The USWCL in Phoenix has adequate laboratory, calibration, and office spaces for conducting this research. In addition to high speed internet and network connections, personal computers are well-equipped with up-to-date word processing, spreadsheet, graphics, and presentation software. Scientists have ready access to SAS statistical analysis software and image processing/analysis packages from ESRI (ARC INFO and ARC View), ERDAS, and ENVI. Specific RS equipment consists of handheld, fixed-mount, and imaging infrared thermometers; an extended-area, black body IRT calibration device; wide- and narrowband radiometers; two portable, high resolution fiber optic spectroradiometers with dedicated field computers and an external integrating sphere; $BaSO_4$ and Spectralon field calibration panels; and digital cameras with visible (Nikon) and red and NIR (Agricultural Digital Camera, Dycam, Inc.) capabilities. The lab shares 4%, 8%, 48%, and 64% canvas calibration tarps with the ARS, Southwest Watershed Research Center in Tucson. The RS team has two differentially corrected GPS units and an Agricultural Irrigation Imaging System (AgIIS, Barnes et al. 2001) on a linear move irrigation boom. The USWCL also has the necessary neutron scattering and TDR equipment for monitoring soil water contents, EM-38 for remote estimates of soil texture and conductivity, and Giddings tractor-mounted hydraulic soil sampler with rotary head, flow meters, and flumes for irrigation measurements. There are leaf area meters, balances, refrigerated spaces, and drying ovens for agronomic measurements, SPAD chlorophyll meters, a plant canopy analyzer and linear PAR sensor for characterizing canopy properties, and pressure bombs, leaf psychrometers, and stem flow gages for determining plant water status. We also have standard micrometeorological instrumentation, 2 Bowen ratio towers, and data loggers for use in this project. A soil mechanics and analytical chemistry lab are available at the USWCL for determining chemical and physical properties of soil and plant samples.

The USWCL maintains an ongoing research support agreement with the Maricopa Agricultural Center (MAC), 30 miles south of Phoenix, which is an 1800-acre agricultural research and demonstration facility of The University of Arizona. The MAC facility is fully equipped and staffed for managing a variety of crops simultaneously. It has ready access to irrigation water from the local Irrigation and Drainage District. Field plot experiments will be conducted on the research portion of the facility, whereas large-scale experiments will be conducted on commercial-sized fields available on the demonstration portion. Pending funding approval, all of the USWCL facilities will be relocated to MAC on or about 2005.

The experiments we propose to satisfy goals in each of the three objectives will be planned and executed by the entire RS team consisting of 4.0 Category 1 SYs, 1.0 Category 3 SY, and 3.7 technicians. Dr. Pinter will take the lead role in the Crop Response Objective, assisted by Drs.

Fitzgerald, Barnes, and Wall, Support Scientist Tom Clarke (0.4), and 1.5 FTE technicians. The Irrigation Scheduling Objective will be lead by Dr. Hunsaker with assistance from Drs. Pinter, Barnes, and Fitzgerald, and Kimball, Support Scientist Tom Clarke (0.3), and 1.3 FTE technicians. Leadership in the Precision Agriculture Objective will rest with Dr. Barnes, with help from Drs. Pinter, Fitzgerald, Kimball, Adamsen, Support Scientist Tom Clarke (0.3) and 0.9 FTE technicians. Technical assistance will be supplemented during the field season by temporary employees.

Milestones and Expected Outcomes

Date	Research Objective or Area of Study		
	1. Crop Response	2. Irrigation Scheduling	3. Precision Agriculture
Oct. 2001	Scheduled Starting Time for Project		
Jan. 2002	· Concept paper on two dimensional indices (CCCI, WDI) written and submitted to journal (Clarke, Barnes, Pinter) · Manuscript on fAPAR and spectra from prev. FACE Expts. written and submitted to journal (Pinter) · Data from 2001 LiMIE Broccoli experiment used to confirm CCCI approach for detecting N stress in vegetable crop (Barnes, Clarke, Pinter) · Contingent on NASA funding to FACE Alfalfa CO_2 by H_2O experiment, crop planted (fall 2001), RS measurements underway. (Pinter, Kimball)	· Review and analyze spectral crop coefficient and ET_a/ET_o data from 1985-86 WCL Alfalfa Lysimeter Study. (Hunsaker, Pinter) · Ditto for FACE Cotton with goal of obtaining working spectral K_{cb} algorithms (Hunsaker, Pinter, Kimball, Wall) · Finalize experimental strategy for field tests of FAO-56 WDI and K_{cb} scheduling in cotton (All) · Develop and field test backpack radiometer/micromet pkg coupled with GPS for collecting ground-based georeferenced crop coef and WDI data. (Clarke)	· Journal paper incorporating CWSI index into CERES Wheat model written. (Barnes Pinter) · Cooperative research with Mississippi underway, preliminary results from 2001 LiMIE Cotton Experiments tabulated. (Barnes) · Select cotton model amenable to incorporating RS data. (Barnes, Kimball) · Explore approaches for obtaining aerial imagery in Prec Ag (Fitzgerald, Barnes, Clarke, Adamsen) · Test spatial interpolation techniques on existing images.
Jan. 2003	· Complete cotton experiment designed to validate WDI and CCCI. Tabulate, reduce, and analyze data. (All) · Analyze hyperspectral and CCCI data from FACE Wheat CO_2 by Nitrogen experiment (Pinter, Clarke) · Plan field plot study to answer specific questions in using spectral or thermal indices to detect water, nutrient, or pest stress	· Paper(s) summarizing crop coefficient findings for alfalfa & cotton written and submitted to journal (Hunsaker, Pinter) · 1st cotton irrigation experiment completed (Oct 2002), data tabulated and reduced (All) · Refine protocol as needed for 2nd cotton irrigation experiment	· Growth, yield, and water content from cotton field experiment used to validate prec ag approach using cotton model.

Jan. 2004	· Paper on use of CCCI or comparable index for monitoring N stress in wheat written and submitted to Journal. (Clarke, Pinter)	· 2nd cotton irrigation experiment completed, Oct 2003) data tabulated and reduced. (All) · Finalize experimental strategy for field tests of FAO-56 WDI and K_{cb} scheduling in wheat (All) · 1st wheat irrigation scheduling experiment begun (Nov 2003) (All)	· Growth, yield, and water content from wheat field experiment used to validate prec ag approach using CERES model. · Manuscript on "directed" sampling methods using RS data written. (Barnes et al.)
Jan 2005	· Paper validating CCCI or comparable index for monitoring N stress in cotton written and submitted to Journal. (All) · Data analysis, publication, and presentation of results as significant outcomes arise. (All)	· 1st wheat experiment completed (May 2004), data reduced, tabulated, and analyzed (All) · Refine protocol as needed for 2nd wheat irrigation experiment · 2nd wheat irrigation experiment begun (Nov 2004) (All)	· Paper on techniques for incorporating RS into cotton growth model written and submitted to journal. (Barnes, et al.)
Jan 2006	· Data analysis, publication, and presentation of results as significant outcomes arise. (All)	· 2nd wheat experiment completed (May 2005), data reduced, tabulated, and analyzed (All) · Publication and presentation of results (All)	· Data analysis, publication, and presentation of results as significant outcomes arise.
Sept. 2006	End of Proposed Project Plan		

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GERMPLASM IMPROVEMENT AND AGRONOMIC DEVELOPMENT OF NEW /ALTERNATIVE INDUSTRIAL CROPS

Terry A. Coffelt, Research Geneticist
David A. Dierig, Research Geneticist
Francis S. Nakayama, Research Chemist

PROJECT SUMMARY

Agricultural diversification is important for achieving economic stability and future growth of agriculture. One way to achieve diversification is the development of new crops. New/alternative crops must complement instead of compete with existing traditional crops. In addition, the new crops must be able to conserve water and nutrients and help in improving the environment. The objectives of this project are to (1) acquire and characterize germplasm of promising new/alternative crops; (2) evaluate and enhance new crop germplasm for industrial materials; (3) develop basic knowledge of floral biology, seed production, and plant responses to environmental stresses; (4) develop economical production systems for new crops under various environmental and management conditions; and (5) develop methods for efficient guayule latex extraction and seed oil analyses for characterizing latex, resin, and oil properties. This research will result in scientific and popular publications on the basic biology, characteristics, production systems, and methodology for evaluating, enhancing, and growing new crops. The long-term goal is to provide high yielding germplasm of new crops that is adaptable to a variety of environments and has materials needed for industrial uses. This CRIS is the lead USDA-ARS project for breeding, genetics, germplasm collection, germplasm evaluation, and germplasm enhancement of new crops, and is the major source of the raw materials needed for pursuing related work on product development and utilization. The development of guayule as a new crop would provide relief to the 6 % of the US population with allergies to Hevea latex products. This includes 40 % of the medical workers and 60 % of multiple surgery cases. It would also develop a domestic source of latex, reducing our dependence on imported rubber. Development of additional products from the bagasse could result in additional products such as insulation, termite and wood rot resistant wood products, and a new natural gum base to use in chewing gums. Development of lesquerella as a new crop would result in a domestic source of hydroxy fatty acid, replacing castor oil imports that cost over $100 million annually. The oil would serve as base for renewable based lubricating oils.

OBJECTIVES

1. Acquire and characterize germplasm of guayule, lesquerella, vernonia, and other promising new/alternative crops.

2. Evaluate and enhance germplasm of new crops for industrial materials.

3. Develop basic knowledge of floral biology, seed production and plant responses to environmental stresses.

4. Develop economical production systems for new crops under various environmental and management conditions.

5. Develop methods for efficient guayule latex extraction and seed oil analyses for characterizing latex, resin, and oil properties.

NEED FOR RESEARCH

Description of the Problem to be Solved

The need exists for improving the economic status of the U.S. farmer and reducing the costs associated with surplus crops. In addition, improving this country's balance of payment and decreasing its vulnerability to imports of strategic industrial raw materials cannot be readily dismissed. Successful commercialization of the new crops may even lead to the export of the raw and finished products. Agricultural diversification is important for achieving economic stability and future growth of agriculture. New/alternative crops must complement instead of compete with existing traditional crops. In addition, the new crops must be able to conserve water and nutrients and help in improving the environment.

The U.S. spends over one billion dollars annually importing Hevea rubber - the only source of natural rubber for use in industry and commerce. More recently, it was discovered that a large portion of the world population has become allergic to the Hevea rubber hygienic products. These allergies can sometimes be life-threatening. Guayule (*Parthenium argentatum*) synthesizes latex rubber, which has been found to be hypoallergenic and offers an alternative to Hevea latex. Since the plant is native to the southwestern United States, cultivation of this crop could mean additional economic sources for the farmers in this region. Successful commercialization of guayule, however, depends on the identification and development of acceptable production practices and processing methods. While much is presently known about maximizing solid rubber production, little is known about maximizing latex production.

The U.S. imports over 40 million dollars of castor oil, a strategic raw material, annually for use in lubricants, cosmetics, plasticizers, protective coatings, surfactants, and pharmaceuticals. Production of castor in the U.S. is restricted because of its high level of allergic reactions and seed toxicity. Lesquerella (*Lesquerella fendleri*), a plant native to the U.S., produces a hydroxy fatty acid, which is an acceptable alternative to castor oil. Successful commercialization of lesquerella depends on the identification and development of enhanced germplasm with high seed yields, high oil content, high lesquerolic acid content, autofertility, and acceptable production practices. A large germplasm collection is being developed and evaluated for desirable characteristics at the U.S. Water Conservation Laboratory. Much work remains to be done to finish the evaluation of the collection and to transfer the desired traits into commercially acceptable lines. Information is also needed on optimizing production practices.

The oil-based paint and pesticide industries are looking for ways to reduce emissions of volatile organic compounds (VOC), which contribute to the pollution of the atmosphere. One alternative to correct this problem is to use vegetable oils high in epoxy fatty acids. Vernonia (*Vernonia galamansis*) is one of the few plants that naturally synthesizes an epoxy fatty acid, which has low

volatility and good solvent properties needed in paints. Other industrial uses for the oil are in epoxy-alkyd paints, toughened epoxy resins, dibasic acids, lubricants, pesticides, and adhesives. Successful commercialization of vernonia depends on the development of germplasm with high yield and oil content, high vernolic acid content, good seed retention, uniform maturity, day neutral flower induction as well as acceptable crop production features.

Information available on the cultural management of these new crops is incomplete. Thus, additional work must be done to obtain answers before wide-scale commercial production is possible. Some examples of areas needing work are dates of planting for maximum stand establishment and yield, seeding rates that are economical, seed treatments to ensure stands and break dormancy, planting methods that result in acceptable stands and result in maximum yields, dates of harvest for maximum yield and quality, harvesting methods that result in minimum losses, water use data for scheduling irrigations, nutrient requirements that minimize pollution and result in high yields, pest control measures for insect, disease, and weed problems, post-harvest and preprocessing studies to maximize yields and quality.

Relevance to ARS National Program Action Plan

This research involves collecting, evaluating, and enhancing germplasm of new crops, while developing planting, growing, and harvesting systems for producing a profitable crop, which contributes to the Plant Germplasm Conservation and Development National Program. Cooperative research with other scientists leads to commercial and industrial applications for new crops and new analytical methods necessary for making progress in a breeding program. Besides the primary uses of these crops, additional products such as gums, bagasse, resins, and seed meals for animal feed contribute to the New Uses National Program 306.

Potential Benefits

The development of guayule as a new crop would provide relief to the 6 % of the US population with allergies to Hevea latex products. This includes 40 % of the medical workers and 60 % of multiple surgery cases. It would also develop a domestic source of latex, reducing our dependence on imported rubber. Development of additional products from the bagasse could result in additional products such as insulation, termite and wood rot resistant wood products, and a new natural gum base to use in chewing gums. Development of lesquerella as a new crop would result in a domestic source of hydroxy fatty acid, replacing castor oil imports that cost over $100 million annually. The oil would serve as base for renewable based lubricating oils.

Anticipated Products

This research will result in scientific and popular publications on the basic biology, characteristics, production systems, and methodology for evaluating, enhancing, and growing new crops. The long-term goal is to provide high yielding germplasm of new crops that is adaptable to a variety of environments and has materials needed for industrial uses.

Customers

Customers of this research include other scientists, cooperative state extension personnel, regulatory agencies, growers, users of the GRIN system, other federal agencies, and industry.

SCIENTIFIC BACKGROUND

Germplasm improvement and varietal trials have identified lines that have almost double the rubber yield of older lines. Estimates of the amount of genetic diversity within a facultative apomictic populations have shown high amounts of variation from one generation to the next. This variation is due to the facultative (apomixis and sexuality coexisting) nature of guayule. Various breeding strategies have been devised to accommodate this and improve yield characteristics. Reports relative to the cultural management and production of guayule have been completed. In light of the great impact of the hypoallergenic guayule latex, research has been done to determine the extractability and post-harvest handling of the shrubs prior to processing. Specific Cooperative Agreements, based primarily on DOD-Advanced Materials from Renewable Resources, have been established with the University of Arizona and University of Akron to work on latex physical and chemical properties, and analysis. Cooperative work has been maintained with the ARS Western Regional Laboratory on the biological aspects of the latex.

Several new populations of *L. fendleri* have been collected for use in improving seed yields and other related plant characteristics. These populations had not previously been available through the National Plant Germplasm System. New collections are necessary for plant breeding since they may have improved traits over the present germplasm being used. Other species of *Lesquerella* and a closely related genus *Physaria* also have been collected. These species contain seed oil rich in hydroxy fatty acids that could be developed for lesquerella production in different environments. Preliminary evaluations of some of this new material have been completed. This work is partly funded through a grant form USDA, ARS, Plant Exploration Office and was partially funded in the past through a USDA, Alternative Agricultural Research and Commercialization (AARC) Center grant. A feature of this project is the creation of a network of relationships among government and private sector organization The USWCL has been responsible for defining cultural management practices including irrigation timing and amounts, planting and harvesting techniques, as well as the initial research and development that will eventually result in an alternative crop for the U.S. farmers in a relatively short amount of time.

Hybrids have been produced between a variety of *Vernonia galamensis 'petitina'*, that has a day-neutral flowering response, and germplasm with other desirable characteristics. The initial phase of successfully combining these two germplasm sources has been accomplished. These hybrids have been evaluated at this location and at a number other sites across the U.S. Selections better adapted to specific locations have been made. These hybrids are continuing to be developed through breeding and agronomic studies. Grants have also allowed us to evaluate seeds for oil content and the profile

of the fatty acid distribution by the purchases of NMR and gas chromatographic equipment.

Short- and long-term goals are variable depending upon the new crop and its stage of development. Thus, each of the three crops will have certain priorities peculiar to that crop. Short term goals are: (1) development and release of higher yielding guayule, lesquerella, and vernonia germplasm; (2) development of production, harvest, post-harvest, and storage guidelines and recommendations for growers and industry; (3) evaluation and collection of new lesquerella germplasm from the US and Mexico; and (4) develop new uses for primary and secondary products in cooperation with others. The long-term goal for all crops is to provide high yielding germplasm adaptable to a variety of environments with raw materials useful for industry in order to successfully commercialize these new crops. All work will be closely coordinated within the CRIS unit, and between cooperators and industrial users.

Literature Review

A CRIS search was conducted for projects conducting research in the areas of Guayule, Lesqueralla, and Vernonia. Of the 55 projects received, 26 were for projects that have been discontinued before January 1995, 12 were for projects that will expire in CY 1995, and 17 were for projects expiring after January 1996. Twelve of the 17 will expire in CY 1996, in which two are support for the existing CRIS, one is a cooperative project with this project, and the other two are not related to research proposed in this CRIS. These findings indicate the importance of continuing this project for successful development of lesquerella, guayule, and vernonia as new industrial crops. This CRIS is the lead USDA-ARS project for breeding, genetics, germplasm collection, germplasm evaluation, and germplasm enhancement of new crops, and is the major source of the raw materials needed for pursuing related work on product development and utilization.

<u>Guayule</u>

The United States is totally dependent upon Hevea natural rubber from southeast Asia for commerce and defense. The annual importing cost of this critical industrial material is about $1 billion. Guayule, a native to north-central Mexico and southwestern Texas, is capable of synthesizing rubber with properties equivalent to the Hevea plant (Hammond and Polhamus, 1965). In the early 1990s, the wild shrub was harvested and processed for rubber in Mexico. The rubber was used in the manufacture of automobile tires. The rubber was replaced by Hevea because it could be produced cheaper than guayule. However, no reasons exist that would prevent this plant from being grown commercially in the United States. The economics for cultivating guayule have not been good in the past, but the petroleum crisis of the 1970s and the large increase in natural rubber prices in the mid 1990s have greatly improved the possibility for commercialization of the plant.

The recent discovery by an ARS scientist that the rubber from the guayule plant is hypoallergenic has further enhanced the potential for commercializing this crop (Cornish, 1995; Siler and Cornish, 1994). Because of the widespread use of latex products and poor quality control, many people have become allergic to Hevea latex. The allergy can be mild to life threatening and special meetings have been

convened to discuss Hevea allergies (European Rubber Journal and Rubber Consultant meeting, 1993). There appears to be no solution to the allergy problem with Hevea, since the allergy causing proteins present cannot be completely removed without affecting the quality of the ruber products. Thus, there is a tremendous market for guayule latex for the production of medical products such as catheters, surgical gloves, contraceptives, balloons, and toys. The use of guayule latex could generate a larger economic impact than that of guayule rubber for tire production. Resins, another major natural product of the guayule plant, hold promise for developing co-products such as adhesives, coatings, and biological control agents, which may have an economic value equal to or greater than the natural rubber (Bultman et al., 1991; Thames and Kaleem, 1991; Nakayama et al., 1992).

Guayule rubber extraction to obtain and maintain the latex form has not been seriously considered, since the ultimate goal of removing the guayule rubber was to get it in the solid form. Unlike Hevea, the guayule rubber particles reside in individual cells and must be physically removed from the cells. For getting solid or bulk rubber, the procedure is to grind the shrub and treat it with an organic solvent to dissolve out the rubber from the ground material. In the case of latex, which is an emulsion of suspended rubber particles, a different procedure must be used. Thus, methods must be developed to extract and preserve the emulsified form of rubber. The latex extraction process is less drastic than organic solvent extraction of bulk rubber removal since it is water based. Actually, a procedure for extracting latex with water was made in the mid 1940s, but the object at that time was primarily to remove rubber from the plant and get it into the solid rather than the latex form (Jones, 1948). The solid rubber produced in this manner contained resin impurities, which could be removed by solvent extraction/washing. However, the introduction of an organic solvent into a rubber latex emulsion to remove the resin material would immediately cause coagulation of the latex and formation of solid rubber. This cannot be allowed in the production of latex-based products such as gloves that depend on the formation of a film from the latex.

The resinous impurities in rubber are known to lower the physical quality of solid rubber and would be expected to be true also for latex rubber products (Winkler and Stephens, 1978). Thus, these must be removed but must be done with procedures which would avoid the use of organic solvents. Some of the water soluble and extractable resin-related materials have been identified (Schloman and Hilton, 1991), but those directly related to the rubber particles of the latex have not and must be determined. Industrial standards for guayule latex quality have not been established, but probably would closely follow those for Hevea latex.

Guayule cultivation has never been done on a large and continuous scale, but knowledge on its culture has been developed through the years. Information on its latest management practices has been compiled in a book edited by Whitworth and Whitehead (1991). However, little is known about growing guayule for latex production. Because the principles of latex and solid rubber extractions are different, information is needed about the harvesting, handling, and storage of the shrub. For example, we found that the drying of the harvested shrub can greatly affect the extractability of the latex (Nakayama, 1995). Also, data are needed on the handling and storage of the latex material after extraction. Formulations needed to construct the final latex products must be developed, but the manufacturer at this time would be best able to handle this aspect of product fabrication.

The plant breeding and genetic efforts on guayule for the 1942-1959 period have been summarized by Hammond and Polhamus (1965). Conventional breeding of guayule is hampered by the presence of apomixis in most polyploid material and by self-incompatibility in most sexual diploids. These constraints also have limited the amount of current knowledge on the heritability of economically important characters. Thompson and Ray (1988) and Estilai and Ray (1991) have thoroughly reviewed many of the aspects for improving guayule through breeding and management practices.

Numerous researchers have found a high degree of variability within and between guayule lines (Ray, 1983, 1989; Benitez and Kuruvadi, 1985; Naqvi, 1985; Thompson et al., 1988; Dierig et al., 1989a, 1989b; Thompson et al., 1990b; Estilai and Ray, 1991). Several of these studies have also shown that plant dry weight is generally a better predictor of final rubber or resin yield than either the rubber or resin percentage. These results indicate that significant improvements in plant dry weight, rubber yield, and latex yield should be possible.

The better rubber yielding lines in the Uniform Regional Varietal Trials have been selected and replanted for additional testing and seed increase. Because of the facultative apomictic nature of reproduction in guayule improvement of germplasm through traditional breeding methods is difficult. Tissue culture technology has been developed for clonal propagation of guayule (Radin et al, 1982, 1985). Initial studies been made on the characterization of isozymes in guayule (Estiali et al., 1990; Ray et al., 1993). Development of isozyme patterns in guayule would be helpful for the identification of sexual hybrids in crosses among apomictic parents.

Lesquerella

Domestication of *Lesquerella* species as a new crop for arid lands and a domestic source of hydroxy fatty acids has been discussed (Hinman, 1984, 1986; Princen, 1979, 1982, 1983; Princen and Rothfus, 1984; Senft, 1988; Thompson, 1985, 1988, 1989, 1990a; Thompson and Dierig, 1988; Thompson et al., 1989; Thompson, 1990). Rapid progress is being made toward full commercialization with cooperation between industry and government agencies (Dierig, et al., 1993). Lesquerella is a new World genus of annual, biennial, and perennial herbs. Over 90 species have been described (Barclay et al, 1962; Rollins and Shaw, 1973). The basic chromosome numbers for species within the genus are n=5, 6, 8, and 9 (Rollins and Shaw, 1973). Rollins and Solbrig (1973) demonstrated that interspecific hybridization occurs in nature among some taxa of Lesquerella. This indicated that controlled crossing among selected species many permit transfer of desirable genes and result in genetic recombinations that may be amenable to breeding and selection. However, a sporophytic multiple allele incompatibility system was found to be operative in lesquerella, which may place constraints on transfer of genetic factors (Rollins and Shaw, 1973; Rollins and Solbrig, 1973; Sampson, 1958). Several putative male sterile plants of *L. fendleri* have been observed.

The chemical composition of lesquerolic acid in lesquerella seed oil is very similar to that of ricinoleic acid in castor oil, and is seen as a viable replacement for imported castor oil. Because the carbon chain length of lesquerolic acid is longer than that of ricinoleic acid (C20 vs C18), the possibility exists that lesquerella oil may also prove to be more useful than castor oil in the formulation of new

industrial products. About 95% of lipstick is currently being made from castor oil and part of this can be readily replaced with lesquerella oil. Research indicates that when lesquerella seed oil containing lesquerolic acid is polymerized to form polyesters or polyurethanes in the presence of polystyrene, a new class of tough plastics (interpenetrating polymer networks) is formed (Sperling and Manson, 1983). The two other types of hydroxy fatty acids, auricolic and densipolic acid, found in various lesquerella species, may also prove to be valuable industrial feedstocks for the development of new, unique products.

As with other members of the Brassica family, glucosinolates are present in lesquerella seed meals, but none were found that give rise to goitrogenic substances (Daxenbichler et al., 1962). Seed meals resemble those of other Brassicaceae such as rapeseed and crambe. Lysine contents were found to be significantly higher than those of 41 other species of Brassicaceae, which suggest that they may serve as good protein supplements for feed grains (Miller et al., 1962). A specific glucosinolate (methylsulfinylpropyl isothiocyanate) found in *L. flendleri, L. gordonii,* and other species is believed to have anti-cancerous tumor activity, and is currently under investigation at the University of Minnesota (Dr. L. W. Wattenberg, personal communication).

One species native to the arid Southwest, *L. fendleri*, is considered to be the prime candidate for domestication (Gentry and Barclay, 1962). This species is a perennial grown as a winter annual at elevations between 600 and 1800 meters in areas of annual precipitation ranging from 250 to 400 mm. Germplasm evaluations by Thompson (1988) and Dierig et al. (1995) have confirmed the prediction of Gentry and Barclay (1962) that *L. fendleri* contains the best germplasm for development of a new industrial oilseed crop. Fortunately, germination of seeds of *L. fendleri* appears not to be hampered by dormancy as has been found with other species (Bass et al., 1956; Sharir and Gelmond, 1971). A breeding and selection program and initial agronomic research was initiated by USDA-ARS in 1984 in Arizona (Thompson and Dierig, 1994). Thompson and Dierig (1988) and Thompson et al (1989) reported on the yield potential of *L. fendleri*, preliminary results on the effects of plant population, and water usage. Plant populations of around 1 million/ha appear to be optimal. Seasonal water use of about 640 mm has been found to produce good yields of 1700 kg/ha of seed, 30% oil, and 50% of lesquerolic acid. Lesquerella can be produced in a cropping system very similar to wheat or other small grains grown as a winter crop in areas such as central Arizona (Thompson, 1988). Harvest of lesquerella has been successfully accomplished with a standard combine equipped with small-sized screens (Dierig et al, 1993).

Vernonia

Vernolic acid was first discovered in seed oil of *Vernonia anthelminitica* by Gunstone (1954). This species also was identified in the USDA-ARS plant screening program at NCAUR, Peoria, IL, where oil contents of 26.5% were determined (Earle et al., 1960), and the presence of vernolic acid in the amount of 67% was identified (Smith et al., 1959). Substantial research was conducted to develop this plant into a new crop source of epoxy fatty acids used as industrial feedstocks for the coatings and plastic industries (Princen, 1979, 1982, 1983; Princen and Rothfus, 1984). However, there were major constraints to the domestication of this species that forced termination of the research effort.

Vernonia belongs to the Asteraceae (Compositae) family. There are about 1,000 species in the Vernonia genus (Jones, 1977). Plant exploration and collections were attempted in 1966-67 by Smith (1971) for other potential *Vernonia* sp. in Ethiopia, Kenya, Uganda, Tanzania, and South Africa. Prior to this exploration, collections of *V. galamensis* (formerly known as *V. pauciflora*) were made in Ethiopia by Perdue while on another mission in 1964 (Perdue et al., 1986, and Gilbert, 1986). Seeds of this new germplasm contained 42% oil and 73% vernolic acid, which is considerably higher than *V. anthelmintica*.

The important discovery of this germplasm led to a revived interest in the domestication of vernonia as a source of epoxy fatty acids. Additional germplasm has been collected from Malawi, Ghana, Nigeria, and Kenya. Six subspecies are taxonomically recognized, with one containing four distinct botanical varieties (Gilbert, 1986; Jeffrey, 1988). Currently, there are 33 accessions of the taxa available for crop improvement. In 1989, USDA-ARS initiated a major germplasm development program at the U.S. Water Conservation laboratory. Available accessions of *V. galamensis* were characterized in regard to seed oil content, fatty acid composition, seed weights, and chromosome numbers (Thompson et al., 1994a) Germplasm also was grown at other locations in Texas, Louisiana, Arizona, Virginia, Oregon, and Iowa, to determine the extent of variation under different environmental and geographic conditions (Thompson et al., 1994b).

Vernonia can be grown in most areas of the U.S. only in warm seasons, since it is frost sensitive. The germplasm being evaluated flowered only under short day (cool season) conditions, except in one accession, *V. galamensis* ssp. *galamensis* var. *petitiana*. This accession flowered under any photoperiod condition (Phatak et al., 1989). Unfortunately, our evaluations demonstrated that this variety lacked important agronomic characters present in other subspecies and varieties.

To overcome day-length restrictions, a hybridization program to recombine day-neutral flowering with the other desirable growth characteristic was attempted. Thompson et al. (1994c) outlined the successful progress of these crosses. The main emphasis of the present breeding program at USWCL is to further develop yield characteristics of these day-neutral hybrids. Other plant characteristics being investigated include autofertility, non-dormant seed germination, seed retention, and increased uniformity of seed maturity (Dierig and Thompson, 1993). Lipase activity in the seed, capable of hydrolyzing the triglyceride, is also an industry concern (Ayorinde et al., 1993).

Interest also has been revived in vernonia utilization research (Afolabi et al., 1989; Ayorinde et al., 1988, 1989; Carlson et al., 1981; Carlson and Chang, 1985). A pilot plant for extraction of seed oil produced in Zimbabwe has been completed (K. D. Carlson, personal communication), which will provide both oil and meal for further research and evaluation by industry. The low viscosity of vernonia oil may permit it to be used as a solvent or additive to alkyd-resin paints with the expectation that emissions of volatile organic compounds (VOC) will be greatly reduced. VOCs react with nitrogen oxides in the presence of sunlight to crate ground-level ozone, a deleterious component of smog. The more promising uses of vernonia oil for industrial products are baked coatings on metal panels (Carlson et al., 1981), and the synthesis of dibasic acids and interpenetrating polymer networks (Afolabi et al., 1989; Ayorinde et al., 1988, 1989).

APPROACH AND RESEARCH PROCEDURES

The evaluation and development of new-crop germplasm that leads to useful agronomic cultivars with concurrent development of appropriate crop production practices are long-term research activities. Timetables are difficult to construct and frequently inaccurate or misleading even with the most conservative estimates of the problem. Progress toward achieving the objectives will be constantly reviewed and changes made as necessary to maximize efficient use of personnel and resources.

Objective 1 - Acquire and characterize germplasm of guayule, lesquerella, vernonia, and other promising new/alternative crops.

Experimental Design

The success of this breeding program is based on a diverse, well characterized germplasm base. Once this diversity is established, necessary breeding strategies will be implemented to further develop and improve the specific crop. The Germplasm Resources Information System (GRIN) database of the National Plant Germplasm System (NPGS) will be used as a source to identify potential plant diversity. However, in many cases, the available species accessions found in the NPGS do not adequately represent the amount of genetic diversity available in nature. In these cases, new seed collections will be acquired, evaluated, and enhanced. An extensive database has been established for *Lesquerella* and *Physaria* species, which includes extensive locality information from many U.S. herbaria. This database now has over 1400 different entries for collection use.

The goal of our germplasm collections is to obtain genetically diverse plant populations of the potential crop. Related species will also be utilized in crop development and will also need to be collected. Seed will be increased following collection from native areas. Some initial evaluation information will be obtained from original native population sites, and when the seed is increased. Additional evaluation information will be obtained from replicated yield trials when adequate planting seed becomes available. Another important aspect of this objective will be to incorporate these new acquisitions into NPGS. Once accessions are evaluated and characterized, the desired traits will be exploited through breeding strategies.

Contingencies

The successful completion of this object will depend on the continued support by outside funding for collection trips and evaluation and seed increase of germplasm collected. Funding levels will determine whether all three crops can be studied or if studies will be limited to areas that are the most promising. Adequate student and technical help is critical to successful completion of this objective.

Collaborations

Collections and evaluation are coordinated with the Plant Germplasm Introduction and Testing Research Unit, Pullman WA; Regional Plant Introduction Station, Ames IA; and National Seed Storage Laboratory, Fort Collins CO.

Objective 2 - Evaluate and Enhance Germplasm of New Crops for Industrial Raw Materials.

Experimental Design

Standard breeding techniques will be used to develop improved germplasm of each potential new crop. Depending on the floral structure and biology of the crop, different breeding strategies are employed for cop development. Some of these strategies include: (1) improvement of germplasm by half-sib family recurrent selections in open-pollinated populations; (2) incorporation of specific traits, such as day-neutral flowering, from donor plants through backcross breeding; (3) development of lines with natural or chemically inducted mutations for altered seed-oil fatty acid profiles; (4) development of lines through mass, family or single plant selection, as appropriate or wide crosses through intra- and interspecific hybridization to obtain desired recombinations. Lines or cultivars will then evaluated in yield trials at single or multiple locations.

The U.S. Water Conservation Laboratory (USWCL) is equipped to participate in various types of screening and evaluations needed for conducting a breeding program. Seeds can be non-destructively analyzed for oil content by NMR and fatty acid profiles by GC. Assays will be developed for rapid screening for amounts of glucosinolates and seed-coat gums. Work has been done on seed conditioning. Light and dissecting microscopy is routinely performed for cyrological and floral biology information. Haploid production through anther culture or microsporogenesis will be attempted for mutation breeding and generating homozygotes for various genetic studies. Isozyme markers have been identified for various crops and will continue to be used as co-dominant genetic markers. Our laboratory is also equipped for DNA marker analyses, such as RAPD's, utilizing Polymerase Chain Reaction (PCR) techniques.

Contingencies

Successful completion of this objective will depend on being able to achieve the desired crosses between divergent parents within and between species. Funding levels will determine whether all three crops can be studied or if studies will be limited to areas that are the most promising. Adequate student and technical help is critical to successful completion of this objective.

Collaborations

Analyses of other seed oil constituents are at times sent to ARS, USDA, National Center for Agricultural Utilization Research (NCAUR), Peoria IL. We also collaborate with the University of Arizona and the ARS, USDA, Western Regional Research Lab, Albany CA to develop methods to analyze latex, rubber, and resin content of single guayule plants. Collaborations also exist with the National Forest Products Lab, University of Illinois, The University of Arizona, and others in developing uses for guayule bagasse following latex extraction.

Objective 3 - Develop knowledge of floral biology/seed Production and Plant Responses to Stresses

Experimental Design

In order to make hybrids and develop enhanced germplasm, basic knowledge of floral biology such as time of anthesis, degree of autofertility, sterility, day length requirements, seed retention traits, and terminal flowering habits will be developed. Basic studies utilizing accepted and new methodologies and experimental procedures will be used to determine: (1) the amount of autofertility present in the lesquerella germplasm collection; (2) the types and of causes of male sterility, including cytoplasmic, in lesquerella; (3) the day length flowering requirements in the vernonia germplasm collection and hybrid populations; (4) the seed retention traits of guayule, lesquerella, and vernonia; (5) the relationship between head size and yield of vernonia; and (6) the development of terminal flowering habits in vernonia for uniform maturity at harvest.

Successful production of new crops also required knowledge of the crop's response to stress. While the effects of water stress on guayule for rubber production have been determined, similar studies will be conducted to determine the effects on latex production, and seed production in lesquerella and vernonia. Susceptibility to insects and diseases will be evaluated as the need arises utilizing accepted procedures or modifications as necessary. Since guayule and lesquerella are proposed for production in semiarid regions, water requirements and related management studies will be conducted.

Contingencies

Funding levels will determine whether all three crops can be studied or if studies will be limited to areas that are the most promising. Adequate student and technical help is critical to successful completion of this objective.

Collaborations

Cooperative work with the Irrigation and Water Quality group at USWCL, the Remote Sensing unit of the Environmental and Plant Dynamics group, and The University of Arizona will be needed to accomplish this objective.

Objective 4 - Develop Economical Cultural Practices and Production Systems for New Crops under Various Environmental and Management Conditions

Experimental Design

For new crops to become successful, economical cultural practices and production systems must be adequately defined and established. Similarly for the breeding program to be successful these practices and systems must also be specified so that the desired traits can be selected and incorporated into advanced lines. Production practices for solid rubber production for guayule have been developed. However, the effects of these practices on latex production are unknown.

Therefore, tests will be conducted to compare the advantages and disadvantages of direct seeding versus transplants. If transplants are found to be the more desirable practice, the newest field transplanting techniques developed for other crops will be adapted. Concurrently, studies with multiple germplasm lines will be conducted to determine the effects of stem size, time of harvest, and frequency of harvest on latex content. Appropriate field designs and statistical analyses will be used in all experiments. Basic tests will also be conducted to develop production systems for lesquerella and vernonia. Information needed includes fertility levels, optimum plants populations, weed and pest control methods, and planting and harvesting methods. Information developed from these studies will be utilized in the breeding program when selecting parents for developing new populations.

Contingencies

Funding levels will determine whether all three crops can be studied or if studies will be limited to areas that are the most promising. Adequate student and technical help is critical to successful completion of this objective.

Collaborations

Cooperative work with the Irrigation and Water Quality group at USWCL, the Remote Sensing unit of the Environmental and Plant Dynamics group, and The University of Arizona will be needed to accomplish this objective.

Objective 5 - Develop Methods for Efficient Guayule Latex Extraction and /Seed Oil Analysis for Characterizing Latex and Oil Properties

Experimental Design

The development of new crops requires specific extraction and analytical procedures that are not presently available. In addition, the germplasm improvement program will need a vast number of samples to be analyzed and processed rapidly in time for selection and preparation for the next planting cycle. Areas that will need special attention will be sample preparation prior to analysis and automation of the analysis and data reduction. New developments in instrumentation also will be incorporated into the analytical scheme.

A reliable procedure for extracting latex from the guayule shrub is not available at present. Thus, several methods for obtaining latex only will be investigated. The primary procedure being used at present is a water-based process where the shrub is ground with a mixture of antioxidant, resin absorber, and water. The crude latex will be initially cleaned of other plant residue by centrifugation, and the resultant latex will be used for various types of physical and chemical property testing. Preliminary results indicate that the latex must be further purified to remove more of the resin material. The resin material will be analyzed and characterized. Several possible routes to attain acceptable latex purity will be followed. These include solid phase extraction and selective solvent

extraction techniques. All the steps taken from shrub preparation, extraction, and purification of the latex will be carefully evaluated for achieving maximum yields. Latex preparation also will be coordinated with cultural practices, such as time of harvest and methods of shrub storage, in order to maximize latex production.

Contingencies

Funding levels will determine whether studies will be limited to areas that are the most promising or if other possible areas can also be investigated. Adequate student and technical help is critical to successful completion of this objective.

Collaborations

We will collaborate with The University of Arizona and the ARS, USDA, Western Regional Research Lab, Albany CA to develop methods to analyze latex, rubber, and resin content of guayule plants. Collaborations also exist with the National Forest Products Lab, University of Illinois, The University of Arizona, and others in developing uses for guayule bagasse following latex extraction.

Milestones and Expected Outcomes

This project is scheduled for formal review in 2002, thus only three year milestones and expected outcomes are listed.

Date	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
January 2002	New lesquerella germplasm from Mexico will be obtained and seed increased	Guayule germplasm lines will be evaluated for latex and growth	Environmental effects on guayule will be determined	New studies on water use for guayule will be started	Effects of different surfactants on latex extraction will be established
January 2003	New lesquerella germplasm from the US and Mexico will be obtained, evaluated, and seed increased for GRIN system	New lesquerella germplasm lines will be released with higher oil yields	Production system guidelines for lesquerella will be released to growers	Harvesting guidelines for lesquerella will be developed and made available to growers	New products for lesquerella oil will be developed and tested in cooperation with a commercial partner
January 2004	New vernonia germplasm will be released	New higher yielding and faster growing guayule germplasm lines will be released	Production system guidelines for guayule will be released to growers	Production system guidelines for guayule will be developed and made available to growers	New products from guayule bagasse will be developed in cooperation with industry

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Technology Transfer

Following are summaries of the laboratory's major technology transfer accomplishments for 2001.

Irrigation and Water Quality

Scientist: Bert Clemmens – Flow Measurement
Computer software originally developed by Bert Clemmens and John Replogle at the U.S. Water Conservation Laboratory, Phoenix Arizona, and cooperator Rien Bos of the International Institute for Land Reclamation and Improvement (ILRI), The Netherlands, for the design and calibration of long-throated measuring flumes, has been reprogrammed for the Windows environment by Tony Wahl at the Water Resources Research Laboratory of the Bureau of Reclamation, Denver, Colorado. Over the past several years, this software has been downloaded by about 700 individuals representing 54 countries. A new book, *Water Measurement with Flumes and Weirs,* by Clemmens, Wahl, Bos, and Replogle, being published this year by ILRI, provides guidance on design, construction, and calibration of these structures, along with guidance on use of the software.

Scientist: Bert Clemmens – Surface-Drained Level Basins
Level basin irrigation systems that include surface drainage have gained popularity in central Arizona in recent years and, with modification, are expanding rapidly in Louisiana, with more than 10,000 acres converted from sloping irrigation to level basins over the last few years. This technology, originally developed in the early 1980s by Al Dedrick (currently ADA for Natural Resources and Sustainable Agricultural Systems) and Southern Colorado farmer Ves Quinlan, was introduced into Louisiana by farmer Walter Davis with guidance from Al Dedrick and Bert Clemmens. A Davis innovation--"spin ditches" or depressed furrows that allow water to drain off the field surface more effectively--made these basins effective even under high rainfall conditions. Davis and other farmers in the area report 20-40% yield increases with these systems compared to traditional irrigation methods in the area. Clemmens is cooperating with NRCS engineers and local conservationists to verify their functioning and provide design guidelines.

Scientist: Herman Bouwer – Simplified Prediction of Infiltration Rates
Herman Bouwer developed a simple cylinder infiltrometer technique to accurately predict infiltration rates for groundwater recharge basins. Previous infiltrometer techniques were time consuming and inaccurate, due to divergence of flow in the soil away from the cylinder and to limited depth of wetting. The new technique measures and corrects for these phenomena in a simple way, thus yielding values that can be used to design infiltration systems for artificial recharge of groundwater or to predict seepage losses from wetlands or other impoundments. The method was published in 1999 and is now widely used by consultants and project planners with good results. In Arizona during 2001, the method was used by consultants and water districts for proposed recharge projects at the Agua Fria River (Salt River Project), at Lake Powell (National Parks Service), near Casa Grande and Western Maricopa County (private wastewater facilities), the Queen Creek and Chandler areas (for recharge), and the Lake Pleasant area (private development).

Scientist: Herman Bouwer – Predicting and Managing Salt Accumulation and Groundwater Rises in South-Central Arizona

By analyzing regional water and salt balances, Herman Bouwer of the U.S. Water Conservation Laboratory, Phoenix, Arizona, has made long-range predictions about increasing salinity of groundwater and rising groundwater levels in the Phoenix-Tucson region of south-central Arizona. He also pointed out various management procedures to prevent salinity and water logging problems, including groundwater pumping, sequential irrigation of increasingly salt-tolerant crops, reverse osmosis, evaporation ponds, and ultimate ocean disposal or inland storage of brine and salts. The City of Phoenix organized a "salt forum" in the summer of 1999 to present and discuss the issues to the municipalities and irrigation districts involved, and where Herman Bouwer gave an overview of the situation. A grant proposal by ASU and an independent consultant has been submitted in 2001 to the Water Environment Research Foundation for further study of the issues. Dr. Bouwer presented an overview to water and wastewater treatment officials and consultants at a salt panel discussion at the Spring Meeting 2001 of the Arizona Water Pollution Control Association, and consultants have been invited by the City of Phoenix to present proposals for further studies and management strategies with Dr. Bouwer as technical advisor.

Environmental and Plant Dynamics

Scientists: Francis Nakayama & Terry Coffelt – Release of Guayule Latex and Bagasse

Approximately 10 gallons of guayule latex was provided to Yulex Corporation by scientists at the USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona, and Western Regional Research Center, Albany, California. Yulex successfully used the latex to fabricate hypoallergenic films for making medical products. In addition, about 300 pounds of guayule bagasse was transferred to Yulex under a Material Transfer Agreement for their study in the use of this waste product for making insulation materials. Applications were submitted for U.S. and international patents covering the fabrication of guayule composite boards that are termite resistant. The use of the waste products from latex extraction will greatly help the economics and commercialization of the guayule crop.

ARS WEEKLY ACTIVITY REPORTS

Throughout the year scientists submit items for the "ARS Weekly Activity Report. These reports are consolidated at ARS Area level and submitted to ARS headquarters for the information of agency and departmental management.

John Replogle - Measuring and Monitoring Sediment-Laden Streams. Studies completed by engineers at the USDA-ARS U.S. Water Conservation Laboratory (USWCL) in Phoenix AZ will make it possible to measure the flow rates of water in natural streams that carry heavy loads of sediment, a common occurrence in semiarid regions. Flow measurement is essential to controlling and managing flowing water, and even the computer-predictable flow measuring systems now in use become clogged when used in sediment-laden streams. USWCL engineers recognized that there is usually a period near the beginning of a storm flow that can be measured accurately because increasing flow rates tend to temporarily suspend the sediments. Using this information to modify existing flow measuring systems, they have conducted successful tests in cooperation with the California Water Quality Control Board and the University of California at Berkeley to monitor water quantity and quality downstream from a mining site. Additional studies of the concept were conducted simultaneously in a University Arizona thesis project under USWCL supervision. A paper outlining the concepts and results of the field and laboratory studies will be presented July 30 at the International Meeting of the American Society of Agricultural Engineers in Sacramento CA.

Herman Bouwer - ARS and USGS Cooperative Research on Irrigation with Sewage Effluent. Scientists at the USDA-ARS U.S. Water Conservation Laboratory in Phoenix AZ, in cooperation with USGS scientists, have undertaken studies to assess the impact of irrigation with sewage effluent on the underlying groundwater. The practice would seem beneficial to mitigate water shortages and use conflicts. In dry climates, however, the excess irrigation water needed to leach salts and other chemicals out of the root zone can eventually reach the groundwater and make it unfit for drinking. The severity of the problem will be assessed with in-depth laboratory and field studies to determine if the effluent or underlying groundwater requires additional treatment.

Bruce A. Kimball - International Collaboration Focuses on Effects of Increasing Carbon Dioxide (CO_2) on Agricultural Crops. In a study arising from the conference on free-air carbon dioxide enrichment (FACE), held in Tsukuba, Japan, in June 2000, and aided by a 3-month sabbatical in Japan, Dr. Bruce Kimball, Soil Scientist at the U. S. Water Conservation Laboratory, Phoenix AZ, with collaborators from Italy and Japan, has completed an exhaustive examination of free-air CO_2 enrichment (FACE) experiments conducted since 1989 in four countries on eight different crops. The FACE research was conducted to determine the likely effects of the increasing atmospheric CO_2 concentration on the physiology, growth, yield, water use, and soil carbon storage of agricultural crops under open-field conditions. Experiments were conducted in Arizona, Switzerland, Italy, and Japan on the major world food crops wheat, rice, and potatoes, as well as on cotton, sorghum, ryegrass, white clover, and grape. Generally, the elevated CO_2 stimulated growth and yield of all the crops when soil moisture and water were ample, except sorghum, which was stimulated under drought conditions. Soil carbon content appeared to increase, which would tend to slow the rate of

rise of the atmospheric CO_2. Comparisons of the FACE results with those from earlier chamber-based results were consistent, which supports the accuracy of conclusions drawn from both types of data.

Bruce Kimball - Interviewed for the Arizona Republic. Bruce Kimball from the U.S. Water Conservation Laboratory, Phoenix AZ, was interviewed on 19 July 2001 by Mr. Max Jarvan, reporter for the Arizona Republic. Mr. Jarvan wanted to know about plans and proposals to conduct global warming or global change research at Springerville AZ. Dr. Kimball described the large geologic pool of CO2 that exists there and how it could be used to conduct free-air CO2 enrichment (FACE) research on the pinon-juniper rangeland ecosystem in which is situated. Ultimately experiments on cultivated crops could also be done. However, plans are slowed by a lack of funds. A research proposal has been written involving Northern Arizona University, USDA-ARS, The University of Arizona, Arizona State University, and other scientists.

Thomas Clarke - ARS Participates in Cooperative Satellite Calibration. On July 26 and 27, remote sensing specialists from the Agricultural Research Service's U.S. Water Conservation Laboratory in Phoenix AZ and the Southwest Watershed Research Center in Tucson AZ joined forces with personnel from NASA Stennis Space Center and the National Imaging and Mapping Agency in a multiple platform calibration. Images of the University of Arizona's Maricopa Agricultural Center were required from IKONOS, LANDSAT 7, and EO-1 satellites and by aircraft ranging from a Learjet to a powered parachute. Ground crews recorded plant and soil parameters as well as surface reflectances and atmospheric measurements in support of the effort. NASA will use the information to compare the different sensor systems while ARS scientists will evaluate each sensor's suitability for helping growers make better-informed management decisions related to the water, nutrient, and pest needs of their crops.

Douglas Hunsaker - ARS Technical Presentation on Surface Irrigation Fertigation. In early August, ARS scientists with the USDA ARS, U.S. Water Conservation Laboratory, Phoenix AZ presented results from their nitrogen fertigation (adding nitrogen fertilizer to irrigation water) field experiments at the ASAE International Meeting in Sacramento CA. Producers who utilize surface irrigation systems have found fertigation can be a very cost-effective method of applying fertilizer to their fields. However, insufficient scientific data are available to develop appropriate guidelines and practices for applying chemicals to fields in this manner. The presentations provided important information on level basin irrigation showing that fertigation was more effective on furrowed cotton than on flat-planted wheat. The applied irrigation water was more uniform in the cotton while lower uniformity in the wheat led to significant leaching of nitrogen below the crop rooting zone at the upper end of the field and low application rates of nitrogen at the lower end of the field. The implications for the wheat were lower yield and potential environmental concerns about nitrogen leaching below the root zone, indicating the need to provide farmers with improved guidelines and practices for this cost- and labor-saving technology.

Bruce Kimball - Cooperative Research Shows Effects of Increased Carbon Dioxide on the Nutritional and Baking Quality of Wheat. ARS researchers at the U.S. Water Conservation

Laboratory, Phoenix AZ; and Western Wheat Quality Laboratory, Pullman WA, with collaborators from The University of Arizona, have determined the likely consequences of future high levels of atmospheric carbon dioxide (CO_2) concentration on the nutritional and baking quality of wheat, a major world food crop. The grain for testing came from free-air CO2 enrichment (FACE) experiments conducted at ample and limiting levels of irrigation and nitrogen fertilizer. Grain samples from the final harvests were subjected to a battery of nutritional and bread-making quality tests. Water stress improved protein and bread loaf volumes slightly. In contrast, low nitrogen decreased quality drastically with protein decreasing 36% and load volume 26%. At ample water and nitrogen, FACE decreased quality slightly or not at all. However, FACE worsened the deleterious effects of low nitrogen on both protein and loaf volume. Thus, these data suggest that future elevated CO2 concentrations will exacerbate the deleterious effects of low soil nitrogen on grain quality; but with ample fertilizer nitrogen, the effects will be minor.

Norma Duran - ARS Scientist Conducts Collaborative Research with Embrapa/Pantanal. From July 30-August 24, 2001, Norma L. Duran, Microbiologist, U.S. Water Conservation Laboratory, Phoenix AZ participated in a joint research project with the Brazilian Agricultural Research Corporation (Embrapa), Pantanal Research Center (CPAP) in Corumba, Brazil. Funding for the research project came from the state of Mato Grosso do Sul, Brazil, to study microbial communities in different environmental conditions and assess potential problems of mercury contamination in the Pantanal wetlands. She also presented a seminar at Embrapa's center, "The Use of Gene Probe Molecular Methods to Study Microbial Mediated Demethylation and Methylation Processes of Mercury." Results from this project will improve our current understanding of microbial diversity and metabolic range while addressing the global environmental problem of mercury pollution in wetland systems.

Glenn Fitzgerald - ARS and University of Arizona Organize Precision Agriculture Meeting. On August 16, 2001, ARS researchers from the U.S. Water Conservation Laboratory in Phoenix AZ and The University of Arizona NASA space grant extension specialist in geospatial technology met with researchers, extension agents, and other stakeholders to discuss precision agriculture issues in Arizona. The meeting was organized by the ARS and The University of Arizona representatives; and topics included the uses of remote sensing and geographical information systems in precision agriculture, precision tillage, soil spatial variability, barriers to adoption, and technology transfer. A round table discussion provided insights about research needs in Arizona and the potential to implement precision agriculture concepts and technology in Arizona.

Paul Pinter - Carbon Dioxide (CO_2) Enrichment in Open Fields is ISI "Fast-Breaking Paper" for October 2001. The Institute for Scientific Information (ISI) Web of Knowledge has identified a manuscript written by the Global Change Research Team, led by Bruce Kimball, at the ARS, U.S. Water Conservation Laboratory in Phoenix AZ as October's "fast breaking paper" for being the most cited paper in the field of agricultural sciences published in the last two years (http://esi-topics.com/fbp/index.html). The article, "Free-air CO_2 enrichment (FACE): Blower effects on wheat canopy microclimate and plant development," was published in the July 2000 issue of *Agricultural and Forest Meteorology*, 103:319-333. The authorship reflects the multi-agency and international collaboration that characterizes global change research in ARS: P.J. Pinter, Jr., B.A.

Kimball, G.W. Wall, D.J. Hunsaker, F.J. Adamsen (U.S. Water Conservation Lab.), K.F.A. Frumau, H.F. Vugts (Vrije Universiteit, Amsterdam, The Netherlands), G.R. Hendrey, K.F. Lewin, J. Nagy (Brookhaven National Lab., Upton, Long Island NY), H.B. Johnson (ARS, Grassland Soil and Water Research Lab., Temple TX), F. Wechsung (Potsdam Inst. for Climate Impact Research, Potsdam, Germany), S.W. Leavitt, T.L. Thompson, A.D. Matthias, and T.J. Brooks (Univ. of AZ, Tucson). The FACE approach was developed jointly by scientists from ARS and Brookhaven National Laboratory and has provided essential knowledge regarding the potential effects of anticipated increases in atmospheric CO_2 on crop production. This paper identified a limitation in the original design, which led to improvements in FACE operating strategies in the U.S. and around the world.

Francis S. Nakayama - ARS and Cooperators File for Patent on Termite and Wood Rot-Resistant Composite Board. Francis Nakayama, Research Chemist at the U. S. Water Conservation Laboratory in Phoenix, with co-inventors from the University of Illinois, Urbana IL and the Forest Products Laboratory (FPL) in Madison WI have applied for a patent for a composite board, made of otherwise waste plant material from the guayule shrub, that resists termite and wood-rot. The composite board is made from the residual plant material that otherwise would require disposal after the hypoallergenic latex has been extracted from guayule for the manufacture of medical and other products. A demonstration on the use of guayule, a renewable, biobased agricultural crop, is being presented at FPL for its "Madison House: A Construction Laboratory" Open House in October to highlight the uses of guayule's by-products to preserve wood.

Edward M. Barnes - Improved Irrigation Scheduling Using Remote Sensing. ARS scientists at the U. S. Water Conservation Laboratory in Phoenix AZ in cooperation with engineers at The University of Arizona, are using remotely sensed data to improve irrigation scheduling methods for farmers. The result can be higher productivity and profits, lower water use, and less chance of degrading water quality. The new procedures being used to interpret remotely sensed data relate an established crop water stress index an established crop water stress index (CWSI) derived from remotely sensed data with plant available water. In the past, the CWSI has proven a valuable source of information by indicating when there is water stress, but reliable determination of how much irrigation is needed based on the index has not been possible. A link between the CWSI and a soil dryness term already developed for crop water use calculations has been found that now allows the CWSI to be related to soil moisture content. The relationship provided reasonable estimates of soil moisture in a field study with surface irrigated cotton (relatively low irrigation frequency). Further studies are planned to test the relationship for high frequency irrigation systems.

STAFF

U. S. WATER CONSERVATION LABORATORY STAFF

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Arterberry, Carl K.	Agricultural Science Research Technician Soil
Askins, JoAnne	Physical Science Technician
Barnes, Edward M.	Agricultural Engineer
Bautista, Eduardo	Agricultural Engineer
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Lab Director, Supvy Res Hydr Engr
Coffelt, Terry A.	Research Geneticist (Plants)
Colbert, Sharette M.	Physical Science Technician
Conley, Matthew M.	Billogical Science Technician (Plants)
Dahlquist, Gail H.	Agricultural Science Research Technician (Plants)
Dierig, David A.	Research Geneticist (Plants)
Draper, T. Lou	Secretary (Office Automation)
Duran, Norma	Microbiologist
Fitzgerald, Glenn J.	Research Argonomist
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary (Office Automation)
Hunsaker, Douglas J.	Agricultural Engineer
Johnson, Kathy J.	Physical Science Technician
Johnson, Stephanie M.	Biological Science Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
Leake, Greg S.	Biological Science Technician (Plants)
Lewis, Clarence L.	Machinist
Maneely, Suzette M.	Biological Science Technician (Plants)
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Specialist
Nakayama, Francis S.	Research Chemist
Olivieri, Laura M.	Biological Science Technician
Pettit, Dean E.	Electronics Engineer
Pinter, Jr., Paul J.	Research Biologist
Powers, Donald E.	Physical Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rish, Shirley A.	Program Analyst
Rokey, Ric R.	Biological Science Technician (Plants)
Strand, Robert J.	Engineering Technician
Strelkoff, Fedja	Research Hydraulic Engineer/Research
Valdez, Deborah K.	Office Automation Clerk

Vinyard, Stephen H.	Physical Science Technician
Wahlin, Brian T.	Civil Engineer
Wall, Gerard W.	Plant Physiologist

ADMINISTRATIVE OFFICE

Name	Title
Gerard, Robert J.	Maintenance Worker
Hodge, Vanessa J.	Budget and Accounting Assistant
Lee, Richard E.	Custodial Worker
Martin, Kevin R.	Maintenance Mechanic Supervisor
Schoenholz, Jason L.	Maintenance Worker
Sexton, Judith A.	Purchasing Agent
Steele, Terry L.	Safety & Occupational Health Specialist
Wiggett, Michael R.	Administrative Officer
Worthen, Michelle	Office Automation Assistant

TEMPORARY EMPLOYEES

Name	Title
Adam, Neal R.	Plant Physiologist
Amann, Michael A.	Engineer Technician
Ashley, Amy F.	Biological Science Technician
Bishop, Lerey R.	Computer Clerk
Blank, Melissa A.	Biological Science Technician
DeGraw, Christa L.	Office Automation Clerk
DeGraw, Lisa L.	Office Automation Clerk
Eshelman, Trathferd G.	Physical Science Technician
Faber, Amy	Physical Science Technician
Jacob, Sally J.	Biological Science Aid
Jerman, James A.	Physical Science Aid
Lanison, John C.	Biological Science Aid
Luckett, William E.	Physical Science Technician
Marcil, Marie A.	Physical Science Aid
O'Brien, Jessica L.	Physical Science Aid
Schmidt, Baran V.	Computer Programmer Specialist
Tabbara, Hadi	Soil Scientist
Tomasi, Pernell M.	Biological Science Technician
Vu, Duong H.T.	Engineering Technician

TEMPORARY STATE EMPLOYEES

Name	Title
O'Brien, Carrie C.	Research Laboratory Assistant (Staff)
Richards, Stacy	Biological Science Aid
Triggs, Jonathan	Biological Science Aid

COOPERATORS

UNIVERSITIES

Arizona State University	Tempe, Arizona
Department of Civil and Environmental Engineering	
Department of Geography	
Department of Plant Biology	
Plant Biology	
California Polytechnic State University	San Luis Obispo, California
Kansas State University	Manhattan, Kansas
Michigan State University	East Lansing, Michigan
Mississippi State Univeristy	Starkville, Mississippi
Dept of Agricultural & Biological Engineering	
New Mexico State University	Las Cruces, New Mexico
Northern Arizona University	Flagstaff, Arizona
Northwest Agriculture University	Yangling, Shaanxi, China.
Peter-Gules van Overloop, van Overloop Consultancy	The Netherlands
Texas A&M University	Lubbock/Pecos, Texas
Agriculture Experiment Station	
Universidad Autonoma Agraraia Antonio Narro (UAAAN)	Saltillo, Mexico
Universita della Tuscia	Viterbo, Italy
Universitat Autonoma	Barcelona, Spain
University of Akron	Akron, Ohio
Department of Chemistry	
University of Alberta	Edmonton, Canada
University of Arizona	Tucson, Arizona
Dept of Agri & Biosystems Engineering	"
Dept. of Entomology	"
Dept of Plant Sciences	"
Dept of Soil, Water & Env Science	"
Laboratory of Tree-Ring Research	"
Maricopa Agriculture Center	Maricopa, Arizona
Marana Agricultural Center	Marana, Arizona
Maricopa County Extension Service	Phoenix, Arizona
Yuma Agricultural Center	Yuma, Arizona
University of Colorado	Boulder, Colorado
University of Essex	Colchester, United Kingdom
University of Florence	Florence, Italy
University of Florida	Gainesville, Florida
University of Guelph	Guelph, Ontario, Canada
University of Illinois	Chicago, Illinois
Natural Resources and Environmental Sciences	Urbana, Illinois
University of Mississippi	Stoneville, Mississippi

University of Montana	Missoula, Montana
University of Nebraska	Lincoln, Nebraska
Dept of Biological Systems Engineering	
University of Queensland	Gatton, Queensland, Australia
Virginia State University	Petersburg, Virginia
Virginia Tech Univ-Virginia Agric Exp Station	Suffolk, Virginia
Vrie Universiteit of Amsterdam, University of Amsterdam	Amsterdam, Netherlands

STATE, COUNTY, AND CITY AGENCIES

California Water Quality Control Board	Oakland, California & Sacramento, California
Imperial Irrigation District	Imperial, California
City of Surprise	Surprise, Arizona
City of Tolleson	Tolleson, Arizona
Maricopa Country Extension Service	Phoenix, Arizona

FEDERAL LABORATORIES

Brookhaven National Laboratory	Upton, New York
NASA Goddard Institute for Space Studies	New York, New York
NASA, Stennis Space Center	Stennis, Mississippi
National Germplasm Resources Laboratory	Beltsville, Maryland
Natural Resources Conservation Service	Portland, Oregon
National Water and Climate Center	Little Rock, Arkansas
National Water Management Center	Phoenix, Arizona
U.S. Department of Energy	Washington, DC
Environmental Sciences Division	
USDI-USGS	Tucson, Arizona
USDA-ARS, Citrus and Subtropical Products Laboratory	Winter Haven, Florida
USDA-ARS, Grassland Protection Research	Temple, Texas
USDA-ARS, National Soil Dynamics Laboratory	Auburn, Alabama
USDA-ARS, Northwest Irrigation and Soils Res Laboratory	Kimberly, Idaho
USDA-ARS, Plant Germplasm Introduction Station	Pullman, Washington
USDA-ARS, U.S. Salinity Laboratory	Riverside, California
USDA-ARS, South Central Agricultural Research Lab	Lane, Oklahoma
USDA-ARS, Southwest Watershed Research Lab	Tucson, Arizona
USDA-ARS, Western Wheat Quality Laboratory	Pullman, Washington
USDA-ARS, National Center for Agricultural Utilization Res	Peoria, Illinois
USDA-ARS, Western Regional Research Center	Albany, California
USDA-ARS, National Center for Genetic Resources Preservation	Ft. Collins, Colorado
USDA-Forest Products Laboratory	Madison, Wisconsin

OTHER

Agriculture & Agri-Food Canada Horticultural R&D Centre	Quebec, Canada
Agricultural Research Council of South Africa	Elsenberg, South Africa
Automata, Inc.	Nevada City, California
Center for the Study of Carbon Dioxide and Global Change	Tempe, Arizona
Citrus Research and Education Center	Lake Alfred, Florida
GCTE (Global Change Terrestrial Ecosystems) Wheat Network	Oxon, United Kingdom
IMTA (Mexican Institute for Water Technology)	Cuernavaca, Mexico
Maricopa-Stanfield Irrigation & Drainage District	Stanfield, Arizona
National Institute of Agro-Environmental Sciences	Tsukuba, Japan
Potsdam Institute for Climate Impact Research	Potsdam, Germany
Salt River Project	Phoenix, Arizona
Yulex, Corp.	Philadelphia, Pennsylvania